Technology Research

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The Hydrogen Economy

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Highlights

- Despite near universal optimism for the hydrogen economy, we believe it is improbable that hydrogen will become a major energy carrier within the next 25 years because future resources could be put to more effective use directly, without significant involvement of hydrogen or fuel cell technology. Such progress would reduce demand for fossil fuels and mitigate the environmental impact of widespread use of such fuels for non-transportation applications.
- The predominant challenge faced by proponents of the hydrogen economy is the unfortunate reality that hydrogen is not a fuel source but an energy carrier, much like electricity. As such, more energy will be required to create, compress/and or liquefy, and transport hydrogen than will be available at the point of consumption. While production losses are typical with any energy source or carrier, in most instances the energy source for hydrogen, whether it is produced from hydrocarbons, electricity, or in any other means, is directly useable without the associated losses. As such, the 'well to wheels' efficiency gains of, for example, Proton Exchange Membrane fuel cells, are comparatively modest when compared to more immediately applicable technologies such as hybrid electric vehicles.
- While we do not presume to prescribe solutions to anticipated calamities wrought by global warming, air pollution and energy shortages, we believe straightforward public policy moves—such as investing in mass transit infrastructure, banning two stroke engines, and differentially taxing wasteful products such as linear power supplies used in electronic gadgetry—would not only be more cost effective than deploying a global hydrogen infrastructure, but also more likely to actually work.

Please refer to pages 39 to 40 for Disclosure Statements, including the Analyst's Certification.

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Investment Conclusion

We worked towards initiating coverage of the hydrogen energy sector for a number of months. We spent countless hours investigating the comparative merits of various fuel cell technologies, power conversion schemes, hydrogen distribution challenges, and other issues directly and even obliquely related to the "hydrogen economy". We read books on the subject, and factored environmental concerns about greenhouse gases and air pollution into our assumptions about growth in demand for various types of fuel cells.

It is worth noting that, beside legitimate hydrogen economy related companies, there exists a posse of hangers on who write books and articles on the industry, grant interviews, lobby governments, and give speeches on the subject. In addition, the idea of a pollution free world fuelled by, "… clean hydrogen, which produces clean water as a by product …" draws politicians like bees to honey, and these politicians make headlines by granting money to various hydrogen and fuel cell related projects.

In short, the amount of information on the subject is virtually unlimited, and one could work full time on the Sisyphean task of simply keeping track of developments in this industry. While we have not kept a tally, there is a consistent thread in the data, and that is the view, which, if not unanimous, then certainly held by an overwhelming majority of experts, that the world of the future will be fueled by hydrogen. The only question for investors appears to be how one invests in that future. Oftentimes, the answer to that question is spun into research reports of a hundred pages or more, covering the most minute detail of fuel cell technology.

Unfortunately, as is often our hard lot to relate, we have concluded that this view is mistaken. Although we arrived at that conclusion after months of work, we have spent even more time trying to construct a simple explanation as to why we believe that, unless antipathy towards nuclear (fission) power changes completely almost immediately, or unless dramatic strides in nuclear fusion are made, we are virtually certain that we will not see widespread use of hydrogen, or fuel cells, in transportation applications in our lifetime, or even this century.

Any investment thesis, in particular one that runs contrary to consensus, must be concise or it will go unread and unconsidered. That is why we experimented with various analogies, and simplified explanations, as well as drawings and other explanatory aids for quite some time in an effort to articulate our conclusion. This puts us at a tremendous disadvantage. Clever people such as scientists and energy experts continuously hammer home the simple, easy to understand and concise dogma of the hydrogen economy. One can almost incant the catch phrases: hydrogen is the most abundant element in the universe; hydrogen offers clean energy; fuels cells are the most efficient way to produce electricity; there are no greenhouse gas emissions; and on and on.

The problem, as Noam Chomsky once pointed out, is that some ideas do not lend themselves to concision. We cannot explain in 10, or even 100 words, why the pro-hydrogen experts are wrong. Besides, it is always challenging to disprove a widely-held theory. The best we can hope to do is to offer the framework for our argument, and hope the momentum of that exercise bears fruit. Here it goes.

Hydrogen is the most common element in the universe, but on planet Earth it is only found combined with oxygen (as in water), carbon (as in organic compounds), or other elements. One will never drill a hole in the ground and 'discover' elemental hydrogen. Hydrogen can be produced provided one is willing to apply enough energy to liberate it, therefore it is an 'energy carrier', not an energy source. The most common method of producing hydrogen is steam reformation of natural gas, which consumes the non-renewable resource and produces greenhouse gas as well as hydrogen. Production of hydrogen from electricity or thermal cycling is only 'clean' to the extent that the energy source is 'clean'; therefore, a hydrogen economy would be more environmentally benign only to the extent the energy sources used to produce, compress and distribute hydrogen are benign. This truth has little to do with the merits of hydrogen or technological advances in fuel cell design. Furthermore, energy losses associated with hydrogen production, compression and/or liquefaction, and distribution may not ultimately offset the enhanced efficiency of fuel cells.

The prime enabler of the hydrogen economy is not advancement in fuel cells as much as advancements in environmentally friendly and cost effective energy production technologies such as wind and solar power, or nuclear alternatives. For example, consider the development of an ideal energy source such as a fusion reactor design, which is inherently safe and environmentally benign and which could not be used to produce the ingredients for nuclear weapons. Realistically, such a reactor would be a large project and take some time to build, and even if the fuel costs were low, capital and distribution costs would still yield electricity rates above the 'too low to meter' threshold.

Even if the production costs of this ideal energy source were well below the cheapest alternative today, it would only set the stage for a hydrogen economy; that is because the best use of the energy, from either an economic or environmental perspective, no matter what the nature of this new source, would be to use it to replace the output of all existing coal fired generating plants, then the oil fired plants, then the natural gas fired plants, then the old fission reactors. Next, it would be best to discourage use of natural gas and oil for home and industrial heating, and so on until every point of energy consumption by stationary systems was completely replaced by fusion generated electricity. This process alone would take decades. Only then would it make economic and environmental sense to look at producing, compressing and distributing hydrogen for planes, trains and automobiles, by which time the price of traditional fuels such as gasoline and diesel would almost certainly be a fraction of current levels.

By eliminating fossil fuel use in electrical generation and stationary uses, greenhouse gas and air pollution levels would be well below where they currently are. Both the decline in fuel prices and the mitigation of environmental effects would reduce the impetus to transition to a hydrogen economy—at least until energy reserves became tight, which would happen farther into the future by virtue of reduced consumption levels.

In other words, the focus of the hydrogen economy industry, whether motivated by profit or environmental concerns, should be first and foremost on the question of where the energy is expected to come from. While arguments can be made that the energy efficiency of fuel cells may ultimately be better than that for traditional engines of today on a 'well to wheels basis', it is not certain that it will be the case when one compares as yet undeveloped fuel cells with as yet unperfected alternatives such as hybrid electric vehicles.

The hardest argument to counter in favour of a hydrogen economy is that it offers flexibility because hydrogen can be derived from many sources and if (or when) an environmentally benign energy source is developed, hydrogen production can simply shift to that alternative. While this 'build it and they will come' rationale has some allure, it requires the sort of forward thinking that governments, investors and consumers are rarely faulted for possessing. Besides, it would be a pity if hundreds of billions of dollars was spent on the various hydrogen economy components such as vehicles, hydrogen production and distribution, and so on, immediately prior to the development of (for example) a 'super battery' or other disruptive innovation. In any event, as we noted above, if indeed such an energy source were developed, the cheapest and best use would not be to produce hydrogen but to generate electricity to replace existing stationary energy requirements.

What makes this analysis particularly troubling, setting aside the fact that it is roughly the opposite of the consensus view of investors, scientists, industry leaders and environmentalists alike, is that it is not a valuation call, nor does it make any assumptions regarding the relative merits of various fuel cell technologies, hydrogen distribution schemes, technological innovation, and so forth, because none of those matter. We believe that recommending any investment in the hydrogen economy presupposes that industry and society at large consciously act in a manner counter to their economic best interests and to the best interests of the environment in general.

Unfortunately, therefore, we believe investors would be investing in the idea of a hydrogen fuelled economy, not in the economic benefits that might accrue to certain players as a result of a transition to a hydrogen economy because, as explained above, we believe such a transition is exceedingly unlikely within the next few decades, or even in this century. This is a situation that does not lend itself to financial analysis, modeling or valuation.

Of course, it is worthwhile to consider the possibility that our analysis is faulty and that the net economic/environmental benefits of using fuels cells are positive even after discounting the need for significant scientific and technological progress, as well as the investment of large sums of money in hydrogen production and distribution. Even then, any valuation model for any participant in the sector would be so sensitive to forecasting parameters that a slight change to any single assumption such as the cost of capital, pace of adoption, cost of goods sold, and so on, would cause wild swings in valuation. This would not even include the possibility of competitive dynamics, both favourable and otherwise.

It appears that the consensus valuation mechanism in the hydrogen or fuel cell sector is comparable valuation. This is unfortunate as, in our opinion, the majority of publicly traded 'comparable' companies are not very comparable, and for the most part are overvalued industrial products firms benefiting from the association with hydrogen. In any event, the fundamental underlying problem with relative valuation is that it doesn't consider the possibility that all companies in a sector may be inappropriately valued. (This is probably the most profound, albeit least learnt, lesson of the 'dot com' era.)

Earnings drive valuation, and in the case of any hydrogen economy related investment we could provide any target price one desires through subtle adjustment of our forecasting parameters. Because investment recommendations should be driven by the relationship between current share price and potential (target) share price, we can equivalently justify any such recommendation though minor changes in parameters. With respect to target price setting, companies in the sector are rather simply un-analyzable.

Unfortunately, this is a message that nobody with even an oblique interest in the hydrogen economy wants to hear. We can almost hear the howls of outrage. Nevertheless, it is a message that somebody has to deliver. The conclusion remains whether or not a major auto company invests another hundred million dollars in the project (it is worth comparing the total global R&D investment in hydrogen powered vehicles to date with the promotional budget of a single auto manufacturer); whether another politician announces funding for ‘alternative energy’ (while simultaneously maintaining several orders of magnitude of more support for coal powered generation); or whether another pop-environmentalist writes a book or test drives a hydrogen powered vehicle: we believe it’s not going to happen.

The Promise of Fuel Cells

Any study of the hydrogen economy must begin and end with low temperature fuel cells in transportation applications. Although there are promising applications for fuel cells in stationary power generation, most such high temperature units can digest a variety of fuels directly (and therefore don't need elemental hydrogen) and are not applicable for transportation applications due to long start up times and safety concerns. Non-fuel cell use of hydrogen in transportation is possible as every space shuttle launch demonstrates, and while running an internal combustion engine off hydrogen is possible, it is unclear what possible advantage would accrue from doing so. Similarly, while non-transportation applications of low temperature fuel cells exist, applications that would benefit from somewhat higher efficiencies, quicker start up times, and low noise/low emissions and still support the much greater system and fuel costs are probably quite few.

Understanding fuel cells requires an understanding of electricity and the peculiar characteristics of hydrogen. The most basic atom in the universe is hydrogen, which consists of a single proton and an electron. A proton is a positively charged particle, while an electron is negatively charged. Separating positive from negative charges creates a difference in electrical potential, or a voltage, and the flow of electrical charge across a voltage is a current. All of the electronic and electrical devices we use apply moving electric currents or voltages to generate light, turn motors, make sound, and so on, irrespective of how the electricity is generated.

Electricity is commonly generated mechanically with a generator whereby a rotating winding generates a current, or chemically with batteries where electrical energy is produced through chemical reactions. Neither process is particularly efficient, but they have been used on an industrial scale and significantly power the modern world.

Fuel cells produce electricity directly from hydrogen by separating the electrons from the protons, thus creating a potential difference. Useful power is produced when current flows around the fuel to permit the protons to combine with oxygen to produce water. Conceptually, a fuel cell is like a battery that uses hydrogen as a fuel and produces power as long as the fuel is available. In principal, the direct conversion of hydrogen to electricity can be quite efficient because it is more or less direct—although it is worth noting that the efficiencies involved in fuel cells, hydrogen production and related matters are bounded by thermodynamics, as are the efficiencies of traditional engines.

Prototype vehicles equipped with fuel cells come in two basic variants, namely direct fuel cell powered, where the sole source of electric power is the fuel cell vehicle (FCV), or hybrid electric FCV (HEFCV), where issues associated with slow start up and poor low temperature performance of an FCV is mitigated by onboard batteries. Fuel is either stored as compressed gas or liquid (cryogenic) hydrogen, as a compressed or liquid hydrocarbon that is 'reformed' onboard into hydrogen, or in a chemical hydride.

The ability to directly produce electricity from hydrogen and produce only pure water as a waste product is the stuff of dreams for environmentalists: because all other atoms are produced from hydrogen via nuclear fusion, hydrogen is the most abundant element in the universe, so we won't run out of it any time soon.

Unfortunately, on planet Earth hydrogen is almost always found combined with oxygen in water or with other elements and it requires a considerable amount of energy to produce free hydrogen gas. The most commonly used process for producing hydrogen is by steam reforming natural gas, so the vision of a hydrogen economy free of dependence on fossil fuels is inaccurate. Such misperceptions are common: for example, one often hears of 'Zero Emissions Vehicles' (ZEV), which are typically battery powered, and therefore not in any meaningful sense 'Zero Emissions' unless one chooses to ignore where the electricity comes from.

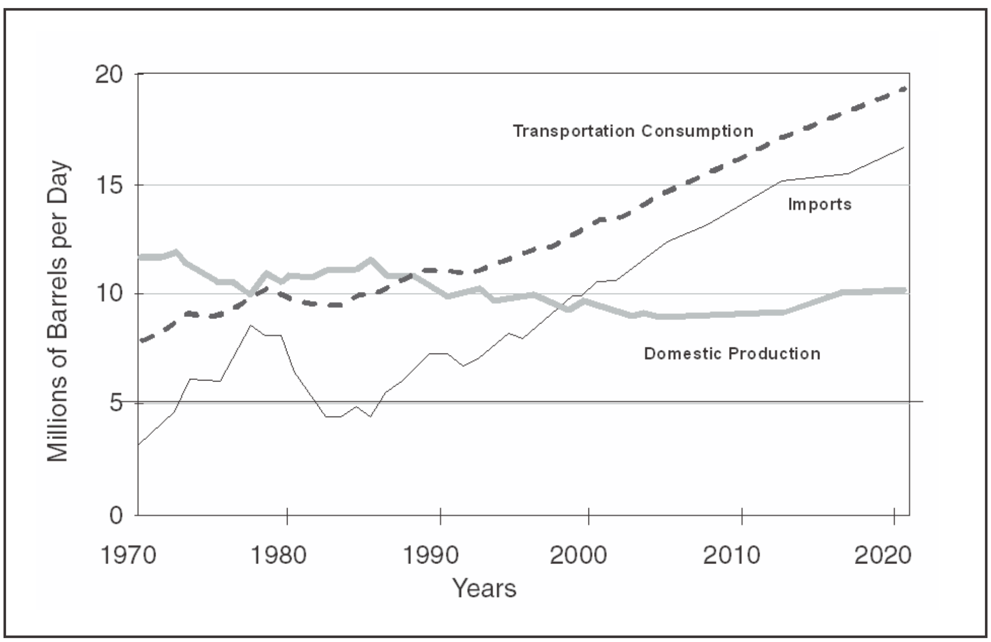
Nonetheless, there is some merit to the idea that the transition to a hydrogen fuelled economy would be the first step of many to a clean energy future. At a minimum, the performance and emissions of centrally located hydrogen production sites could be better regulated and controlled than could millions of privately owned vehicles.

Because fuel cells powered by hydrogen can provide clean, emission free energy, hydrogen powered fuel cells are receiving a large amount of public attention. This is most likely due to rising concerns over energy security, greenhouse gas emissions (global warming concerns), and air quality.

Strengthen Energy Security

The use of hydrogen derived from a variety of domestically available sources, including fossil fuels, renewable sources and nuclear power, could help reduce demand for foreign oil, especially for transportation applications. The U.S. alone uses about 20 million barrels of oil per day with approximately half of that used to produce gasoline for use in automobiles. The consumption of petroleum will only grow as the global economy grows, and almost certainly exceed efforts to expand traditional sources of domestic production. With the transportation sector being the primary driver of petroleum demand, it is estimated that by 2020, U.S. imports of petroleum will need to rise by more than 50 percent, assuming no dramatic breakthroughs are introduced in vehicle technology.

Chart 1: *U.S. Daily Oil Consumption 1970–2020E*



Source: ttp://www.eere.energy.gov

With the growing dependence on imports, the U.S. faces increased political and economic risks because so much of the world's proven oil reserves lie in the volatile Persian Gulf region and importing oil contributes significantly to the trade deficit.

Given the infrastructure exists to store, transport and distribute petroleum, we believe there are technologically less risky and more cost effective methods to improve the nations energy security, than by moving from a carbon economy to a hydrogen one. One method would be to simply improve the fuel efficiency of vehicles. Not only would this help mitigate oil consumption, it would also help reduce pollution and CO_2 emissions as well.

The development of synthetic petroleum fuels from biomass (such as bio-ethanol and bio-diesel) to run our automobiles could also help improve energy security. Bio-fuels are cost competitive with hydrogen, because they can be stored, transported and distributed using existing infrastructure, are technologically less risky, can be introduced much faster and do not lead to increased levels of CO_2 because growing plants process CO_2 into plant matter. Many studies point out, however, that finite agricultural resources such as arable land, water, and so on, limit the potential for bio-fuels to replace only a modest proportion of energy needs.

Reduce Greenhouse Gas Emissions

The greenhouse effect is the name applied to the process that causes the surface of the earth to be warmer than it would otherwise be in the absence of an atmosphere. The greenhouse effect and global warming are two different things. If it were not for the greenhouse effect, the earth would be 30 degrees cooler than it is at present. Global warming is the name given to the increase in the greenhouse effect caused by the increasing emissions of greenhouse gases into the atmosphere, leading to rising temperatures.

The natural greenhouse gases carbon dioxide (CO_2), water vapour (H_2O), nitrous oxide (N_2O), methane (CH_4) and ozone (O_3) are essential to support life. These gases absorb some of the energy that is reflected off the surface of the earth from the sun, retaining heat and warming the planet somewhat like the glass panels of a greenhouse.

With the exception of water vapour, carbon dioxide is the most plentiful greenhouse gas in our atmosphere. Natural sources of CO_2 include animal, bacteriological and plant respiration (plants generate CO_2 at night), burning fuels such as grass and wood, and volcanic activity. Most scientists believe that, since the beginning of the industrial revolution, atmospheric concentrations of carbon dioxide have increased nearly 30% and methane concentrations have more than doubled.

It is widely believed that the primary source of increased concentration of greenhouse gases, and in particular increased levels of CO_2, in the atmosphere is human activity caused by burning fossil fuels such as coal, petroleum and natural gas. These increases have increased the heat trapping capability of the earth's atmosphere, a situation that has been exacerbated by clearing forests, particularly in tropical regions, which play a large part in cleaning the CO_2 from the atmosphere. Depending on the rate of uptake by the different sink processes, CO_2 emitted by human activities may remain in the atmosphere for as long as 50 to 200 years.

Most climate scientists believe that the world's average temperature has risen by 1°F since the 19th century and that the added CO_2 from burning fossil fuels has caused the global mean temperature to increase. While scientists broadly accept the principles of global warming, there exists some disagreement in the scientific community in terms of the quantification of much of the data. The dispute arises because there are concerns about the accuracy of the data and the fact that temperature measurements made using different instruments are often contradictory, particularly those made in the past two decades.

Fuel cells can reduce the production of CO_2 in two ways. If hydrogen used in the fuel cell is produced in a manner that does not itself produce CO_2 (for example, using electricity generated by nuclear, solar or wind power), or through renewal sources such as ethanol produced from corn, then no net CO_2 is produced. Even if the hydrogen is produced from natural gas (which is the common method today) then net CO_2 emissions will be reduced to the extent that the overall efficiency of the 'well-to-wheels' path is such that less CO_2 is produced than through alternative means such as burning the natural gas directly. As we show later in the report, 'well-to-wheels' analyses are rather equivocal on the extent to which fuel cells will reduce CO_2 emissions when compared with developments in more mundane power systems.

Reduce Air Pollution

Power plants burning fossil fuels are the largest U.S. source of anthropogenic greenhouse gases, producing about 2.5 billion tons of greenhouse gases every year. Automobiles are the second largest U.S. source at pumping out approximately 1.4 billion tons into the atmosphere each year. Aside from CO_2 and water vapour (which are not toxic gases), the major products of combustion include partially combusted fuel—hydrocarbons and particulate matter, carbon monoxide (CO), and the oxides of nitrogen (NO_x) and Sulphur (SO_x). Sulphur dioxide and nitrogen oxides are the primary causes of acid rain.

Table 1: *Emissions from U.S. Electricity and Transportation*

		SO_x Emissions			NO_x Emissions		
	CO_2 (% of Total)	Percentage (of Total)	SO_2 per GJ of fuel (kg SO_2/GJ)		Percentage (% of Total)	NO_2 per GJ of fuel (kg NO_2/GJ)	
			Current	Est. 2010*		Current	Est. 2010*
Sector							
Cars and Light Trucks	19	1	0.02	< 0.005	18	0.25	0.01
Other Transportation	14	5	0.08		39	0.70	
Fossil Fuel Electricity	41	70	0.40	0.28	32	0.24	0.12

* Emission rates in 2010 are based on pending emission regulations
Source: www.sciencemag.org (Vol. 301, July 2003)

By decreasing the combustion temperature in automobiles one can reduce the nitrogen oxide emissions, but this leads to increased emissions of non-combusted fuel and particulate matter. Baked by sunlight, this non-combusted fuel reacts with NO_x and other pollutants to form smog (low level ozone), which has been shown to pose a significant threat to public health. Fuel cells powered by pure hydrogen, however, emit no pollutants. Automobiles that use an onboard reformer to convert gasoline, methanol or natural gas to hydrogen do emit small amounts of pollutants (CO) although much less than from burning fossil fuels directly.

Even though automobiles powered by hydrogen could essentially eliminate vehicular emissions, it has been estimated that the cost of reducing NO_x in this manner will be on the order of \$1 million per tonne NO_2. In contrast, meeting new higher emissions standards proposed by the EPA for automobiles by 2010 (Table 1) in conjunction with the necessary inspection and maintenance programs would cost \$6,000 per tonne. And by offering bounties to those car owners whose old and poorly maintained cars produce most of the air pollution (10% of cars produce 90% of emissions), the cost, all in, would be \$20,000 per tonne. The cost of reducing NO_x emissions from fossil fuel electricity is estimated to be in the same range as is the cost of reducing other important air pollutants.

Similarly, a major source of unburned and partially burned fuel is the two-stroke engine, commonly found in garden equipment, outboard motors, personal watercraft and other recreational products. The inefficient (and largely unregulated) design of these engines result in their discarding a significant proportion (25% to 30%) of unburned fuel into the environment. Furthermore, by all accounts, these inexpensive engines contribute disproportionately to virtually all forms of air pollution, in some cases producing significantly more emissions (in absolute terms) in an hour than a car generates in a year.

In almost all applications where a two-stroke engine is used, a four-cycle engine, which is slightly more expensive but has better fuel economy and significantly reduced toxic emissions, can be used. In other words, an outright ban on two-stroke engines would have a major impact on air pollution, with only a minor impact associated with increased costs to consumers. Such a ban could be implemented today, and not require technological developments, inventions and so on.

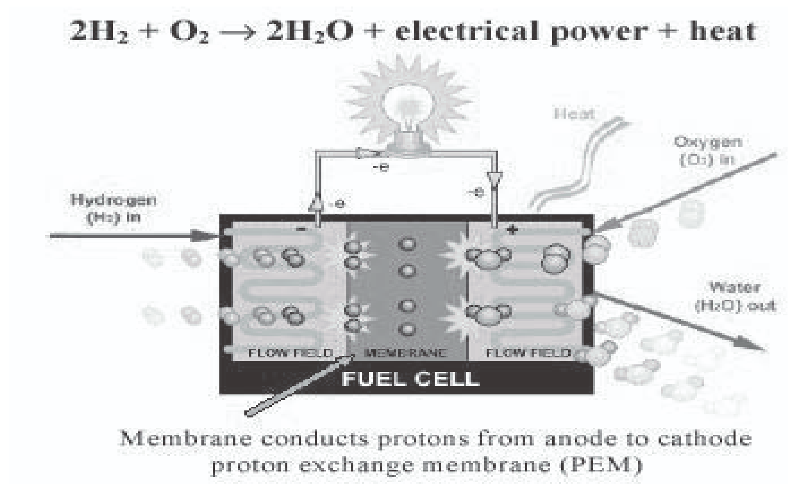
Despite the obvious benefits of such a ban, there isn't one in place and large volumes of two-stroke powered tools and toys are sold every year, and continue to excessively contribute to air pollution. The lack of interest or concern by consumers, industry or government, is representative to us that environmental concerns are frequently more an issue of political correctness than anything else.

So while a hydrogen economy may be one way of improving air quality, it is not the only way, the most cost effective, nor the easiest to implement. While hydrogen powered vehicles would eliminate some problems, we believe improved emission standards, in conjunction with roadside monitoring and other techniques, provide for a more cost effective solution.

How a Fuel Cell Works

At their most basic level, fuel cells combine oxygen and hydrogen electrochemically to produce water, electricity and heat. At the heart of a fuel cell lies an electrolyte that can only be crossed by H+ ions (protons) while being impervious to electrons. Gas-permeable electrodes with a catalyst adhere to this membrane and add a layer to each side of the membrane. These electrodes are in turn connected to a device that can utilize the electricity, a load, which creates a complete electrical circuit. By combining hydrogen fuel and oxygen from the air, electricity is formed without combustion of any form. Figure 1 shows a schematic representation of a single fuel cell.

***Figure 1:** Proton Exchange Membrane*



Source: www.eere.energy.gov/hydrogenandfuelcells

Because the electrochemical process occurs over the surface (electrode/electrolyte interface), the performance of a fuel cell is often quoted in terms of current density or Amps per square centimetre. The power (P) expressed in units of watts (W), delivered by a cell is the product of the current density (A/cm$_2$) drawn, the cell area (cm$_2$) and the terminal voltage (V). To build up practical levels of voltage (i.e., to give a full-size electric vehicle adequate acceleration and top speed, about 50-65 kW are needed) and avoid the need to make electrical connections to each individual cell, fuel cells are assembled end-to-end in stacks.

Because the mass and volume of a fuel cell are very important, additional terms are also quoted. The specific power (P/kg) is the ratio of the power produced by a cell to the mass of the cell (kg) while the power density is the ratio of the power produced by a cell to the volume of the cell (m$_3$). High specific power and power density are important for transportation applications to minimize weight and volume, and to minimize cost.

Types of Fuel Cells

Fuel cells are classified primarily by the kind of electrolyte they employ. This determines the kind of chemical reactions that take place in the cell, the kind of catalysts required, the temperature range in which the cell operates, the fuel required, and other factors. These characteristics, in turn, affect the applications for which these cells are most suitable. There are several types of fuel cells under development, each with its own limitations and potential applications. A few of the most promising types include Proton Exchange Membrane (PEMFC), Phosphoric Acid (PAFC), Direct Methanol (DMFC), Alkaline (AFC), Molten Carbonate (MCFC) and Solid Oxide (SOFC) fuel cells.

Table 2: *Summary – Common Fuel Cell Types*

Fuel Cell Type	Electrolyte	Temp.	Efficiency
Proton Exchange Membrane (PEM)	solid polymer membrane	75°C	35–60%
Alkaline (AFC)	potassium hydroxide	< 80°C	50–70%
Direct Methanol (DMFC)	solid polymer membrane	75°C	35–40%
Phosphoric Acid (PAFC)	Phosphorous	210°C	35–50%
Molten Carbonate (MCFC)	Alkali-Carbonates	650°C	40–55%
Solid Oxide (SOFC)	Ceramic Oxide	800–1000°C	45–60%

Source: BMONB, www.rmi.org/sitepages/pid556.php
Note: According to Volvo Truck Corporation, the maximum efficiency of a diesel engine is around 45%, while that of a four-cycle gasoline engine efficiency is around 30%.

Proton Exchange Membrane Fuel Cells

The core of the PEMFC consists of two electrodes, the anode and the cathode, separated by a polymer membrane (a thin plastic film) electrolyte. Each of the electrodes is coated on one side with a platinum catalyst. As hydrogen ions pass through the membrane and, with the help of the platinum catalyst, combine with oxygen and electrons on the cathode side, producing water. The electrons, which cannot pass through the membrane, flow from the anode to the cathode through an external circuit, which consumes the power generated by the cell.

Compared to other types of fuel cells, PEMFC deliver more power for a given volume or weight of fuel cell, which makes them compact and lightweight. In addition, PEMFC operate at relatively low temperatures, around 80°C (176°F) allowing them to start quickly (less warm-up time) and gives them the ability to rapidly respond to changes in the demand for power. A solid electrolyte material, compared to a liquid, also simplifies sealing in the production process, reduces corrosion, and provides for longer cell and stack life.

In terms of disadvantages, PEMFC require a noble-metal catalyst (typically platinum), which adds to system costs (page 16). Like all other fuel cell technologies (except the DMFC), PEM technology requires a fuel processor if operated with hydrogen derived from hydrocarbon or organic fuels. The platinum catalyst is also sensitive to even trace amounts of CO (0.001%), making it necessary to employ an additional reactor in the fuel processing system. This also adds costs, and although less than current gasoline powered-engines, the multi-unit processor releases CO_2, which mitigates some of the environmental promise offered by fuel cells.

Because PEMFCs offer relatively rapid start up times, are quite efficient and relatively safe due to low operating temperatures and lack of dangerous electrolytes, we believe they are the only viable candidates for transportation applications.

Phosphoric Acid Fuel Cells

The Phosphoric Acid Fuel Cell (PAFC) is considered the "first generation" of modern fuel cells. Field-tested as early as the 1970s, PAFC is one of the most mature fuel cell technologies and the first to be used commercially. Being commercialized for stationary power applications, PAFC provide only a modest power density, a deficit that translates into a relatively large volume and weight as well as higher cost. Another disadvantage is that PAFC cannot provide power at ambient temperature but must be preheated to 100°C before current can be drawn. The ability for rapid start-up would, therefore, be very difficult. As the name suggests, PAFC use phosphoric acid as the electrolyte, which is very nasty and harmful stuff.

On the plus side, PAFC operate at temperatures around 200°C (402°F) to 220°C (437°F) which means that they can tolerate a higher level of CO (1%) in the fuel stream than PEM cells. PAFC are 85% efficient when used for co-generation of electricity and heat but less efficient at generating electricity alone (37% to 42%). PAFC are also less powerful than other fuel cells of the same weight and volume. Another drawback of PAFC is that they are very expensive to operate. Like PEM fuel cells, PAFC use an expensive platinum catalyst.

Direct Methanol Fuel Cells

Direct Methanol Fuel Cells (DMFC) utilize a PEM as an electrolyte and produce electricity directly without the need of a fuel reformer. DMFC have been under development for a number of years, typically in configurations similar to PEMFC. The main advantage of DMFC is that the fuel is a liquid (although fed to cells as a vapour), which means that it is easier to store and given the current refuelling infrastructure, easier to transport and supply to the public. DMFC, however, have been handicapped so far by two major problems: poor performance (current density is well below the level required for automotive applications) and diffusion of methanol vapour through the membrane to the air electrode causes a "short-circuit" reaction. The 'cross-over' problem not only reduces fuel utilization efficiency (typically > 30%) but also reduces cell voltage at the cathode, thereby causing an additional loss of energy efficiency.

Motivated by the inherent attractiveness of the technology, many organizations interested in commercializing PEMFC technology have been working to eliminate the problems limiting the prospects of DMFC. We believe there is a significant potential DMFCs will be successfully commercialized for portable, low power applications such as laptop computers and mobile phones.

Alkaline Fuel Cell

Alkaline Fuel Cells (AFC) were first developed for use in the U.S. space program in the 1960s to provide electrical energy and water on board spacecraft. AFC use potassium hydroxide as the electrolyte and can use a variety of non-precious metals as a catalyst at the anode and cathode. While AFC are capable of generating high power densities, AFC are easily poisoned by CO_2. The CO_2 reacts with the electrolyte, poisoning it irreversibly and severely degrading the fuel cell performance. Because it would be impractical to remove CO_2 from the processed fuel stream completely, AFC have essentially been eliminated from consideration in automobile applications.

Molten Carbonate Fuel Cells

Molten Carbonate Fuel Cells (MCFC) evolved from work in the 1960s aimed at producing a fuel cell that would operate directly on coal. MCFC uses a molten carbonate salt mixture as their electrolyte. Because MCFC operate at 600-600°C, these types of fuel cells are candidates for stationary and combined heat and power applications only. The volume and cost of insulation required to maintain the high operating temperatures, almost certainly rules out MCFC for automotive applications. Molten carbonate fuel cells can reach efficiencies approaching 60% (or 85% with cogeneration), considerably higher than the 37–42% of PAFC.

On the positive side, because of the high temperatures in which MCFC operate, MCFC do not require an external reformer, as carbon based fuels are converted to hydrogen within the fuel cell itself in a process called internal reforming. This also means that non-precious metals (nickel) can be used as catalysts at the anode and cathode, further reducing costs. Unlike other fuel cells, MCFC are not prone to CO or CO_2 poisoning, making them attractive for use with gases made from coal.

The primary disadvantage of current MCFC technology, however, is that the higher temperatures enhance corrosion and the breakdown of cell components.

Solid Oxide Fuel Cells

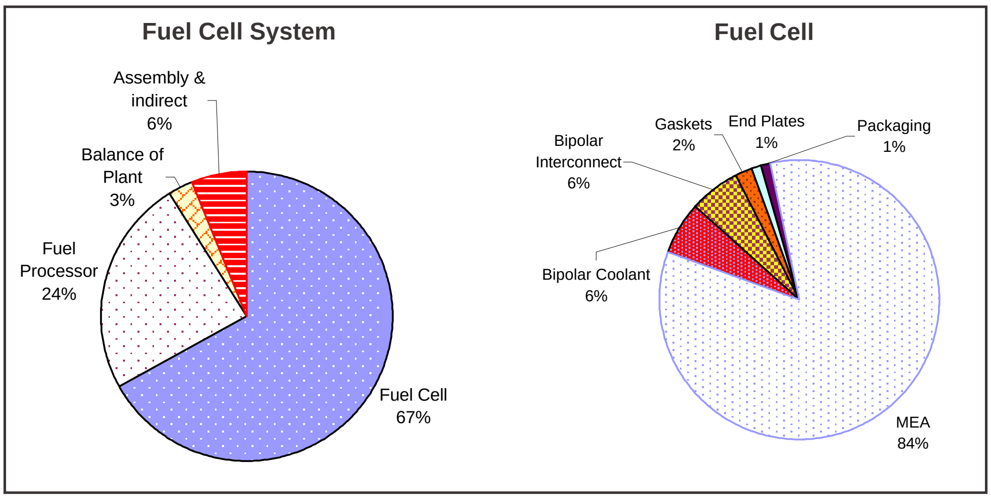
Solid Oxide Fuel Cells (SOFC) use a hard, non-porous ceramic compound as the electrolyte. SOFC are around 50–60% efficient at converting fuel to electricity. In cogeneration applications, overall fuel efficiencies come in around 80–85%. Solid oxide fuel cells operate at temperatures as high as 1,000°C, which removes the need for a precious metal catalyst, thereby reducing cost. It also allows SOFC to reform fuels internally, which enables the use of other fuels.

Key Technical Challenges

As noted above, because of the relatively rapid start up times, efficiencies and safety of PEMFCs, we believe they are the only viable candidates for transportation applications and the technology has been the focus of considerable efforts to improve the cost, power to weight ratio, and durability of PEMFCs. Despite rapid progress in R&D and the technology's promise for the future, there remains significant technical and economic barriers that are expected to keep fuel cell vehicles from making significant market penetration until at least 2020.

The major technical barriers to fuel cell commercialization are the cost and performance of the active materials used within the fuel cell. In terms of cost breakdown, according to recent studies, the fuel processor and fuel cell subsystem dominate the cost of the fuel cell system, even if produced in high volume*.

Chart 2: *Fuel Cell Cost Breakdown (Expected) by Subcomponent*



Source: Cost Analysis of Fuel Cell Powered Stacks/Systems (www.tiax.com)

The Membrane Electrode Assembly (MEA), which is the main component of the fuel cell, is the largest contributor to the cost of the fuel cell system representing approximately 56% of the cost. The high cost of the MEA is derived from the high cost of raw materials (electrocatalyst and PEM) and stack manufacturing costs of the MEA.

* 50 kW engine with 500,000 units/yr. (or approximately 5% of cars sold in the U.S./yr.)

Platinum Cost & Supply

The high MEA cost is the direct result of the use of substantial amounts of platinum (which is very costly and notorious for price volatility) and platinum group metals (PGM). Applied to both the cathode and anode, platinum facilitates the electrode reactions, thereby allowing high currents to be produced in a fuel cell.

Table 3: *Fuel Cell Platinum Loading/Lost*

Component	Autothermal Reactor [1]	Preferential Oxidizer [2]	Tailgas Burner	Fuel Cell MEA	Total Platinum
Weight (g) [3]	9	13	8	181	211
Cost (US$) [4]	$221	$320	$197	$4,450	$5,188

Source: www.tiax.com

Based on the current estimates of cathode and anode platinum loading and a current price of US$24.6/gram (which converts to $697/oz.), and assuming that the platinum component of an MEA accounts for approximately 24% of the total cost of the fuel cell system (as suggested by a recent study), that would put the cost of such a system at approximately US$18,500 or about $330/kW. Even using historically low prices ($14/gram, $400/oz), the cost of the platinum alone would be $2,954 (using historically high prices, $31.75/gram ($900/oz), the cost of the platinum would be $6,700). By comparison, the cost of a power-train (engine, transmission etc.) in a mid-size vehicle is around $3,000. Given the current platinum requirements, these costs are simply unaffordable and too high to support any significant market penetration of fuel cell vehicles. Attainment of future platinum content goals based upon U.S. Department of Energy (DOE) assumptions (while aggressive), however, may enable greater market penetration.

Table 4: *MEA Precious Metal Loading/Cost*

MEA Precious Metal Calculation	Current Reformate	Future Reformate	Future Hydrogen	DOE Goals Reformate
Cathode Pt Loading, mg/cm ^{2}	0.4	0.2	0.2	0.05
Anode Pt Loading, mg/cm ^{2}	0.4	0.1	0.1	0.025
Power Density, mW/cm ^{2}	248	400	600	320
Gross System Power, kW	56	53	53	56
Cathode Pt, g	90	26	18	8.8
Anode Pt, g	90	13	8.8	4.4
Anode Ru, g	45	6.6	0	2.2
Stack Precious Metals	225	46	27	15
Fuel Cell power plant cost (US $/kW)	$330	$75	$12	$24

Source: www.tiax.com

It must be noted that the DOE assumptions relating to platinum content reductions are commensurate with advances in technology to support critical levels of performance (power density and efficiency), which we find difficult to assess.

1 Involves reaction of gasified hydrocarbons with air and steam to produce gas rich in H_2, CO and CO_2
2 Used to reduce CO levels to ppm range (CO reduces fuel cell performance)
3 Current loading requirements (For the Fuel Cell MEA: Power density requirements determine the actual amount of Pt in the system).
4 Based on September 18, 2003 Platinum spot price.

Availability of Platinum for Fuel Cell Vehicles

With the PEM fuel cell being the leading candidate to replace the internal combustion engine in the future, there is some concern about whether the supplies of platinum and other platinum group metals (PGM) will be sufficient to keep up with the demand. The vast majority of platinum is found in just two countries: South Africa and Russia and is used primarily in catalytic converters (to treat car exhaust) and to make jewellery. According to the U.S. Geological survey, the world reserves of PGM are estimated to be approximately 100 million grams (world reserves of platinum are estimated to be approximately 53 million grams).

Assessing the demand for platinum is extremely challenging because these predictions need to encompass a host of factors such as technology development (amount of platinum in an automotive fuel cell), costs (associated with increasing platinum production and platinum market dynamics), economic forecasts (demand for new vehicles in developing countries, costs for power-train systems), market forecasts (of fuel cell and other types of vehicles), industry forecasts (for recycling platinum), geological estimates (of world reserves of platinum), and changes in demand for other applications (demand for platinum jewellery).

According to the International Platinum Association, “there is more than enough platinum to support the widespread introduction of fuel cells for automotive propulsion, stationary power generation or other uses”. Recently, a number of studies published on this issue would suggest otherwise.

Table 5: *Platinum Availability Studies*

Are Platinum Reserves a Barrier to Fuel Cell Adoption?

Study	Assumptions	Results	Barrier?
Rade Doctoral Thesis Chalmers University of Technology & Goteborg University	• 50 kW FCV, 19g/auto, 10 yr. FC life, incl. recycling • FCV introduced sigmoidally to 100 in 2100	• Current reserves depleted in 2053, resources depleted in 2063	YES
Borgwardt U.S. EPA *Transportation Research Part D Journal Article*	• 22g/auto, 15 yr. FC life includes recycling • Platinum production increases at current rate, U.S. demand remains at 16% of world production	• U.S. fleet conversion would take 146 yrs. • If U.S. demand increased to 48% of world production, conversion reduced to 66 yrs.	YES
World Fuel Cell Council (formerly Platinum Association)	• 70kW FCV, 14g/auto, 10 yr. FC life includes recycling • Assumes 1 billion FCVs in 2030 World resources = 1.5 billion troy ounces	• 1 billion car fleet corresponds to 450 million troy ounces of platinum • With 95% recycling, 2 million troy ounces a year required to maintain global fleet	NO
Cawthorn University of WitwatersrandSouth African Journal of Science *Journal Article*	• Does not address fuel cells specifically	• Given present consumption, South Africa reserves will last 40 yrs • If demand increases 6% annually, existing reserves and resources would last 50 yrs	YES

Source: Office of Hydrogen, Fuel Cells, and Infrastructure Technologies - U.S. DoE

Should there be concerns relating to the supply of virgin platinum? We find this question difficult to assess, but most authors suggest that if platinum is not to limit the long-term market penetration of fuel cell powered vehicles, then the development of better and more efficient catalysts must be pursued. Many organizations around the world are presently pursuing this goal.

Membrane Cost

The two most common PEM materials used in the fuel cells are Nafion™, manufactured by DuPont, and the Dow membrane. The main advantage of these materials, aside from their good mechanical and chemical stability is their excellent proton conductance properties. The main drawback, however, is their high price. The cost of a Nafion membrane is about $100/kW. The high cost is due in part to the long preparation process required to manufacture the resin and the fact that the market for resins and membranes, by chemical industry standards, is presently relatively small. However, if PEM fuel cells were eventually accepted in large scale (i.e., in excess of 150,000 PEM fuel cell engines), DuPont estimates that the price will drop to about $10/kW. Ballard Power has developed and patented a lower cost version of the membrane and showed in a laboratory setting that it could perform reliably in a PEM fuel cell in excess of 15,000 hours. These membranes, however, have not yet been shown to be durable to 5,000 hours of operation in the harsh day-to-day environment of an automobile.

Durability

Today's standards for automobile durability call for at least 5,000 hours of operation or 150,000 miles of on-road use. To commercialize PEM fuel cell technology, fuel cell powered vehicles must meet these requirements. In terms of a fuel cell, durability is defined as the ability of the MEA to resist permanent change in performance over time. This is typically associated with membrane failure or catalyst sintering (platinum deactivation from CO or sulphur poisoning) causing power density to decay. Because one important factor in PEMFC durability is the purity of fuel, a practical fuel cell vehicle must be tolerant of impurities in fuel, especially if onboard reformation is used since many hydrocarbons have sulphur impurities. Therefore, unless extremely high purity fuel is provided, some sort of filtration system will be required to completely remove potentially damaging impurities. Such a system will be mission critical because a failure in the filtration system would destroy the fuel cell stack. Contrast this with a traditional automobile engine that is tolerant of impurities and has only a few destructive failure modes.

We know that with continued maintenance, today's internal combustion engines can last a very long time. If consumers are to accept fuel cell vehicles, then longevity of a fuel cell system will be a pivotal consideration.

Cold Weather Performance

Fuel cells contain water for two purposes: for humidifying the cell and as a by product of the electrochemical reaction of hydrogen and oxygen. The gases entering the PEM stack must be humidified to prevent the electrolyte from drying out. As long as the electrolyte remains humidified, the electrolyte acts a near perfect ionic conductor. Too little water and the electrolyte dries out, which could result in hydrogen and/or oxygen crossing over the membrane causing irreversible stack damage as a result of the heat generated in this chemical short-circuit. Cold weather operation, therefore, may be problematic since water, as we all know, freezes at low temperatures. PEM fuel cells must also reach a certain temperature to attain full performance.

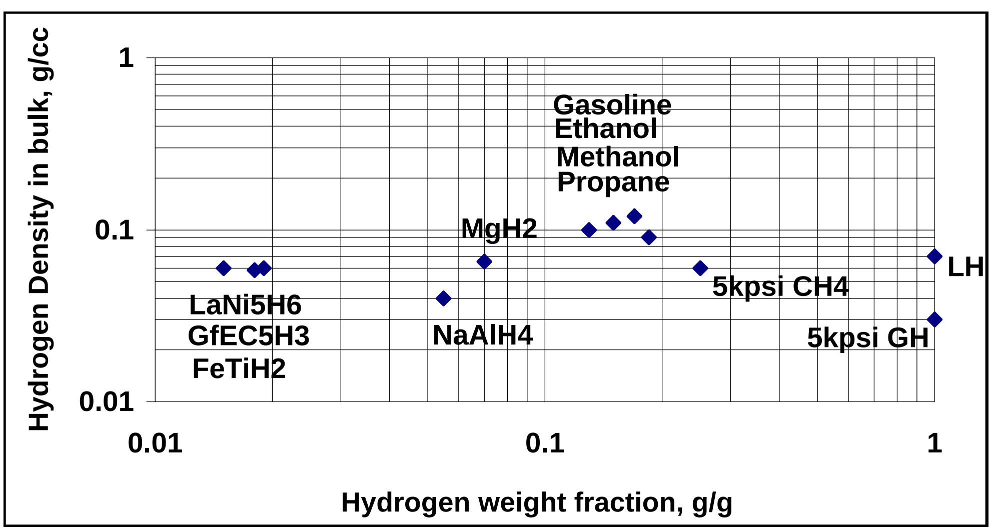
Hydrogen Storage

In order for the general public to buy fuel cell vehicles in large numbers, it is critical that the range of these vehicles be at least as great as the cars we drive today. On a full tank of gas, an average vehicle has a range of about 300 miles (483 km). In terms of fuel cells vehicles, there are presently four different systems for hydrogen storage: high-pressure gas storage, metal hydrides (hydrogen absorbing rear earth metals), liquid hydrogen and reformate.

Even under extremely high pressure (10,000 psi), a fuel tank designed to fit inside the trunk of an automobile can only hold enough hydrogen (7 kg) to provide a fuel cell vehicle with the range of about 170 miles (274 km). This may be less of a concern in the future if new fuel cell automobiles are designed around hydrogen fuel tanks and not vice versa, which is the case presently.

Even though hydrogen gas has a hydrogen weight fraction ratio equal to one (since it's 100% hydrogen), its low weight per volume means that compressed hydrogen gas fuel systems (even under very high pressures) are not able to provide the same driving range as compared to conventional gasoline. Certain metal hydrides on the other hand are very compact, with a third to half the volume compared to a pressurized hydrogen tank (at 5000 psi); however, they are very heavy. An equivalent metal hydride system holding 7 kg of hydrogen would weigh approximately 350 kg. Nevertheless, because metal hydrides are kept at low pressure (less

Chart 3: *Hydrogen Density in Materials*



Source: L.K. Leung, "Using Metal Hydride to Store Hydrogen", Savannah River Technology Center than 200 psi), they are considered to be inherently safer than compressed hydrogen storage.

Compared to gaseous hydrogen, liquid hydrogen occupies a relatively small volume. In fact, the density of liquid hydrogen is comparable to that of many of the hydrides being considered for fuel cell applications. However, to liquefy hydrogen, it has to be cooled down to -253°C (i.e., 20 K), which consumes about one-third of its energy content. In order to provide an effective level of insulation, the walls of the cryo-tank need to be made relatively thick (i.e., 3 cm), which tends to make them costly. Nevertheless, about 1–3% of the hydrogen is lost continuously every day through self-resealing valves that vent the excess pressure caused by warming and evaporation of the liquid hydrogen within the tank.

Another solution to storing hydrogen at high pressure or at cryogenic temperatures on-board a vehicle is to extract the hydrogen from a liquid fuel such as gasoline, methanol or diesel via a fuel reformer. These conventional fuels not only allow use of existing infrastructure but also allow the use of fuels with a higher energy density than pure hydrogen gas. With roughly the same size fuel tank as that of a gasoline powered vehicle, a reformate powered fuel cell vehicle has a driving range that is about 1.5 times longer than one using compressed hydrogen. Fuel cell reformers, however, tend to be rather complex, which tends to make them fairly expensive. Moreover, because of the inherent thermal inefficiencies of the device, fuel processors tend to decrease the overall efficiency of fuel/fuel cell stack.

Competition

There are over 50 companies in North America, Europe and Japan developing PEM fuel cells and PEM fuel cell systems. These companies can be roughly placed in two camps, namely; large automobile manufacturers such as Toyota, General Motors (GM) and Honda; and those such as Ballard Power, which is teamed with Ford and Daimler Chrysler, and everyone else. Some of the many other companies involved in PEM fuel cell development for on-road applications include United Technologies (UTC), which supply fuel cells to Nissan and Hyundai, and Nuvera, a private company that supplies fuel cells to Fiat.

For consumers to come to accept fuel cell powered vehicles, the alternative technology must equal the performance and cost of vehicles powered by gasoline. The big automobile manufacturers are well positioned to meet these goals. For one, they have the financial resources to do so and two, Toyota, GM and Honda are vertically integrated, which gives them the flexibility to optimize the performance (and drive down costs) of the whole vehicle as opposed to UTC and Nuvera, which are attempting to optimize only the performance and cost of the fuel cell stack.

In terms of currently available public information, it seems rather difficult to determine who

Table 6: *Other Fuel Cell Systems Competitors*

	General Motors	Toyota	Honda	Ford	DaimlerChrysler
Market Cap (B$)	24.05	106.6	39.5	23.5	38.3
Fuel Cell Vehicle	HydroGen3	FCHV-4	FCX	FCV-Hybrid	Necar5
Power Output-Fuel Stack (kW)	90	90	80	85	75
Cruising Distance (km)	400	> 250	395	300	200
Maximum Speed (km/hr)	140	> 150	150	130	145
Fuel	Liquid Hydrogen	Compressed H_2	Compressed H_2	Compressed H_2	Methanol

Source: BMO Nesbitt Burns, respective companies among all these competitors is the performance and cost leader since each metric seems to change rapidly and will continue to do so until fuel cell vehicles are commercialized.

While the barriers to entry are very high given that enormous sums must be invested into research and development and production methods, we expect competition to grow in this industry as we get closer to commercialization. This will come not only from competing technologies (substitution for cleaner traditional technologies such natural gas and diesel) but also from the concentration of existing customers (the car companies) as they can be expected to merge into fewer but larger companies.

Well to Wheel Analysis

The traditional approach used to compare the efficiency of vehicles was by the distance they could travel per unit of fuel consumed (mpg or km/l). However, this method presents difficulties especially if the cars being compared run on different fuels such as natural gas or hydrogen. In such cases, we need to use a different measure; one that takes into account not only how efficiently the car uses energy (tank-to-wheel), but one that also measures how efficiently energy is obtained and transported to the car’s tank (well-to-tank). In order to obtain such a

Overall Efficiency <Well-to-Wheel>	=	Fuel-Efficiency <Well-to-Tank>	X	Vehicle Efficiency <Tank-to-Wheel>

measure, the Well-to-Tank (WTT) and Tank-to-Wheel (TTW) components must be integrated. This measure of overall efficiency is called the “Well-to-Wheel” (WTW) method and is given as the product of fuel efficiency (WTT) and vehicle efficiency (TTW).

Many advocates of alternative fuel cell vehicles forget that many fuel cell vehicles actually shift the pollution created from one location to another. While a fuel cell vehicle powered with hydrogen may produce only water and heat as by-products, 95% of the hydrogen (today) actually comes from the steam reformation of fossil fuels. So even though there is no carbon in hydrogen, given its source, hydrogen really isn’t such a clean fuel after all. In order to get a sense of the real amount of greenhouse gas (GHG) emitted, therefore, it is necessary to examine the entire fuel cycle—from creating the fuels, to using them to power the wheels of vehicles.

Two recent studies, one North American and one European, analyzed the well-to-wheel energy use and greenhouse gas emissions (CO_2) for a wide range of fuels and vehicle technologies.

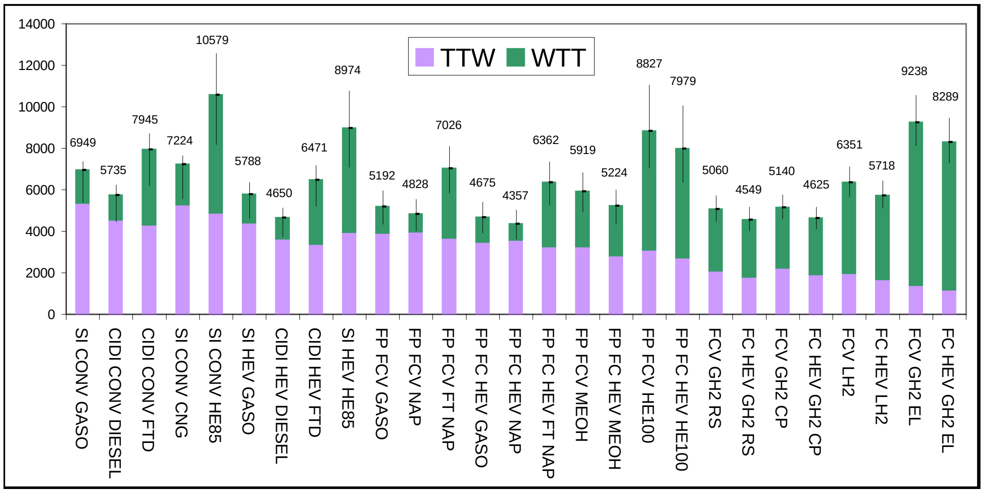
The North American study[1,2] which examined 13 different fuels (from different 75 pathways) and 15 different conventional and advanced vehicle architectures, concluded that the lowest total energy use was achieved with the diesel hybrid electric vehicle (HEV), fuel cell (FC) hybrid electric vehicles powered with naphtha (or gasoline) and hybrid electric fuel cell vehicles using gaseous hydrogen from reformed (non-North American)[3] natural gas. It worth pointing out that Diesel HEV (which are expected to require incremental capital investments to be

[1] Considered North America between the timeframe 2005 and 2010
[2] Did not consider cost, cold-start or transient response but did consider resource availability. All vehicles were required to deliver the same performance - acceleration, top speed and vehicle range
[3] Current and potential North American natural gas resource base is considered insufficient to supply widespread use of natural gas as a transportation fuel in the U.S.

developed but have lower infrastructure costs) are expected to provide comparable performance to FC HEV, which are expected to require enormous capital investments (estimates range from $150–300 billion) to store and deliver the hydrogen to consumers.

Moreover, even though fuel cell vehicles (FCV) using compressed hydrogen reformed from natural gas (FCV GH_2) had better fuel economy than conventional gasoline or diesel vehicles (SI* CONV GASO or SI CIDI** DIESEL), because the production of hydrogen uses more energy then does the production of diesel fuel or gasoline, the energy consumption among

Chart 4: *Well-to-Wheel (WTW) Total Systems Energy Use*



Source: http://www.transportation.anl.gov/pdfs/TA/164.pdf

these options on a well-to-wheel basis was nearly equal. Furthermore, direct methanol powered FCV (which are also being actively considered for commercialization in the future) performed no better in terms of overall efficiency than did reformed gasoline fuel cell vehicles.

It is also interesting to point out that FCV using hydrogen produced via hydrolysis through the current U.S. power mix (FC/HEV GH2 EL) consume significantly more energy than many other pathways. This energy inefficiency is primarily due to the fact that much of the U.S.

Table 7: *Renewable Share of Wheel-to-Tank Total Energy Use*

Fuel	WTT % Renewable
Gasoline	1.7
Diesel	1.8
Crude naptha	1.9
Compressed Natural Gas (CNG)	3.3
Methanol	0.2
Fischer Trope (FT) naptha	0.1
FT Diesel (FTD)	0.1
GH_2 - central plnats	3.8
LH_2 - central plants	0.1
GH_2 - refueling stations	2.2
GH_2 - electrolysis	13.8
Herbaceous (HE) Cellulose 100%	97.3
HE85 (85% HE, 15% Gasoline)	90.6

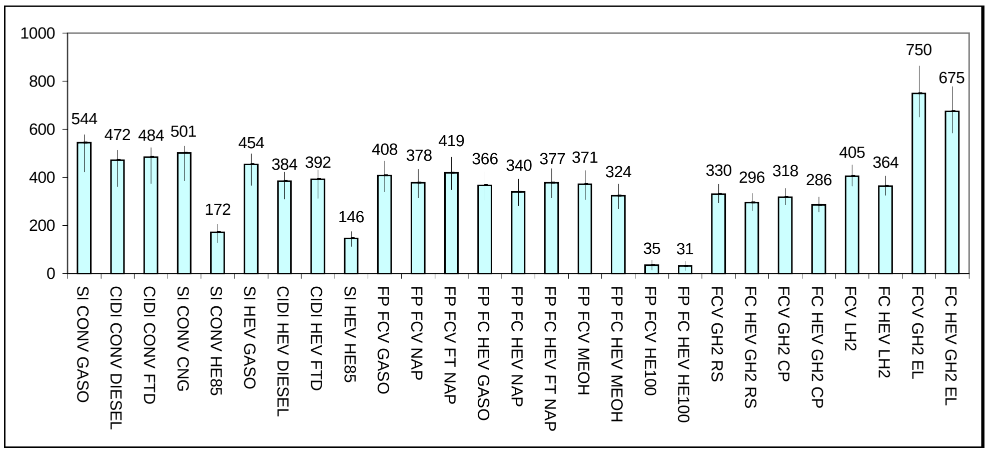
Source: http://www.transportation.anl.gov/pdfs/TA/164.pdf

* SI: Spark Ignition
**CIDI: Compression Ignition Direct Injection

power mix is derived from coal and other fossil fuels. The ethanol vehicle pathways (HE85 and HE100) had the lowest energy efficiency among all the options considered, considerably less than either petroleum or natural gas, although a significant portion of the energy used was renewable.

In terms of Well-to-Wheel greenhouse gas emissions, as expected, vehicles fuelled with ethanol have the lowest equivalent CO_2 emissions (because of carbon uptake) per mile. With the exception of a FC/HEV operated with hydrogen generated via electrolysis using the U.S. power mix (for similar reasons as highlighted above), all the other fuel/vehicle pathways released less CO_2/mile than did conventional gasoline powered vehicles.

***Chart 5:** Well-to-Wheel GHG Emissions Conventional & Hybrid Fuel/Vehicle Pathways*



Source: http://www.transportation.anl.gov/pdfs/TA/164.pdf

While greenhouse gas emissions from HEV operating on hydrogen reformed from natural gas had the lowest CO_2 emissions, it is interesting to point out that similar vehicles operated with fuels other than compressed hydrogen, such as diesel, performed equally well.

The results of the European Well-to-Wheel study were generally found to be consistent with those of the North American WTW analysis in terms of relative rankings of fuel/vehicle pathway combinations. In terms of absolute values, the WTW values were lower, primarily because the Opel Zafira used in Europe was much smaller than the full size Chevrolet Silverado pickup in North America.

The European study favours renewable fuels such as ethanol, which the U.S. study points out are impractical due to the available agricultural capacity.

It's About Energy

Fuel cells are an intriguing technology: the common view is that Hydrogen goes in, and electricity and water comes out. While correct in a general sense, the underlying simplifications take out a lot of the messy details. For example, there are a number of different types of fuel cells ranging from the low temperature PEM units most people think they know about through to nasty sounding molten carbonate constructions targeting industrial power generation.

Each variant of fuel cell has its pros and cons. For example, PEM fuel cells are relatively lightweight and safe enough to be used as the power plant of a relatively flimsy mobile system like a car or truck. Unfortunately, at the current state of the art, PEM fuel cells are expensive and not sufficiently long lived to be considered as a replacement for an internal combustion engine. Furthermore, existing designs use a lot of platinum as a catalyst, require fabulously expensive Proton Exchange Membranes, and are particularly sensitive to the presence of even trace impurities in the gaseous hydrogen fuel required for their operation. Fuel storage is a significant problem: while hydrogen is very light, the volume of gas required for any significant range is immense, and various methods of storing the gas as a liquid or otherwise sequestered are either bulky, heavy, or both. Nonetheless, PEM fuel cells are relatively energy efficient when measured relative to the energy content of the hydrogen fuel, and we believe are probably the only viable fuel cell candidate to replace the internal combustion engine.

Less commonly encountered fuel cells such as phosphoric acid, liquid carbonate and solid oxide operate at significantly greater temperatures than PEM and are, in our opinion, unlikely to be suitable for vehicular operation for no other reason than they are not suitable for 'stop and go' operation in a car or bus. Besides, phosphoric acid is nasty, dangerous stuff, and the prospects of post auto accident exposure to the reagent (which is held at 150 to 200°C) would likely mitigate interest among consumers. Similarly, even short exposure to molten carbonate, held at around 650°C (twice the melting point of lead), is incompatible with life. There are advantages to these high temperature designs: they are efficient (especially when cogenerating heat) and relatively tolerant of fuel impurities (in some cases are able to digest fuels ranging from hydrogen to diesel). We believe the most likely applications of high temperature designs is in relatively large scale stationary power generation.

Any application of fuel cells faces serious obstacles, including the perfection of the technology to the extent that a combination of factors including price, durability and efficiency make the technology a viable alternative to existing alternatives, mostly consisting of various heat engines including reciprocating engines such as gasoline and diesel, turbines, and so on. Of course, this is a moving target as the respective characteristics of these devices will improve with time, especially if manufacturers are working under a competitive threat from fuel cells. However, the efficiency of heat engines is limited by physical principals and they have come a long way.

Although the challenges to developing a commercially successful PEM based automobile could fill a book (and actually have already filled several), these can all be dismissed as mere technological challenges on the way to eventual success. We do not dispute this; there are many clever people in the world and diligent work, and a bit of luck, ultimately yields a solution to problems that are solvable, as we believe the development of a commercially viable PEM fuel cell is. We cannot, however, let slip the opportunity to point out that some of the cleverest minds in the world have been working on developing a commercially viable nuclear fusion reactor for decades now, with only glacial progress. Some solvable problems are easier to solve than others.

Most discussions of fuel cells include some degree of pronouncement upon their superiority from an emissions perspective relative to heat engines. In particular, devices that use hydrogen as a fuel do not emit CO_2, the production of which is targeted by the Kyoto protocol. While this is true, and it is also the case whether the hydrogen is used in a fuel cell or in a heat engine, one has to take into account where the hydrogen came from. In any scenario describing a planned migration to a 'hydrogen economy' hydrogen is expected to be produced from hydrocarbons (fossil fuels) for a long transition period. As a result, the production of CO_2 would be mitigated only to the extent that efficiency gains from the use of hydrogen in efficient fuel cells would not be offset by losses inherent to the production of hydrogen from hydrocarbons.

In other words, the complete transition to a hydrogen economy would not necessarily reduce CO_2 emissions unless the hydrogen is produced in a manner that does not result in a net gain of CO_2 to the environment. Electrolysis (using electricity to split water to produce hydrogen) only fits the bill to the extent that the electricity so generated arises from a 'clean' source such as hydroelectric, wind, solar, geothermal, or nuclear. It is worth noting that the use of nuclear energy remains controversial, to say the least. Alternatively, biomass sources such as making ethanol from corn, which are closed loop systems and therefore do not result in a net gain of CO_2 to the environment could be employed.

We believe the prospects of a clean environment overshadow the major challenge associated with transitioning from a hydrocarbon to a hydrogen based economy, and that is that hydrogen is not an energy source but an energy carrier, unlike hydrocarbons, which effectively are an energy source representing many millions of years of stored solar energy as captured by long dead bacteria, plants and so on.

Another major argument in favour of the hydrogen economy is that the earth is rapidly depleting its fossil fuel reserves. While it is clear that hydrocarbon reserves will eventually run out (the issue, as always, is when), the process will not necessarily be slowed by transition to a hydrogen based economy unless the renewable power sources mentioned above are greatly developed.

In fact, unless fuel cells are developed that are efficient enough to at least offset losses associated with the production, transportation and storage of hydrogen as well as the incremental capital expense required to effect the transition, an argument could be made that the transition will accelerate, rather than slow, the depletion of energy reserves. This is a very big hurdle indeed: even conservative estimates of the cost to transition to a hydrogen economy defy the bounds of everyday discourse.

Of course, the argument can be made that a combination of growing global population, increasing per capita energy use, and finite fossil fuel supplies, necessitates a transition away from fossil fuels in any event, so we had may as well get started. Unfortunately, multidimensional problems such as these rarely present simple one dimensional solutions. In other words, population, energy consumption, energy reserves, and hydrocarbon prices are not independent variables but actually tightly coupled, and worse yet, likely associated in a non-linear fashion.

While there can be no doubt as to whether or not the world requires new sources of energy, there is considerable variability in terms of how quickly these sources will come on line or are required to come on line. As it happens, this analyst has lived most of his life within a chronic state of crisis associated with a combination of energy shortages and looming environmental cataclysm, neither of which has come to pass, thankfully, although that doesn't mean these are not just around the corner, as we are oft reminded.

We are quite willing to believe that the problems associated with developing or exploiting new energy sources will ultimately be solved—as they must be as part of the transition to a hydrogen economy. After all, even the most hard hearted, SUV driving, anti-environmentalist would have trouble expressing a love of smog and higher energy prices. We believe that innovation, along with the needs of the marketplace, will result in broader exploitation of renewable energy sources such as hydro, wind, biomass, geothermal, solar power, and nuclear, either as a result of safer fission reactors, such as those that have already been demonstrated, or eventually, fusion plants.

Where we have a problem, however, is finding a place for hydrogen in this scenario. In virtually every situation we can think of, the development of any energy source that could be used to make hydrogen solves almost all of the problems then and there.

For example, 'green' (for want of a better term) electric power would lower the demand on hydrocarbons for power generation. This would, in turn, reduce emissions of CO_2, as well as smog and other ill effects of hydrocarbon use, irrespective of whether or not the electricity was used directly or indirectly (for example using hydrogen as a carrier) for transportation. If the electricity were available, this could be done with existing technology on the existing grid infrastructure, without requiring much in terms of new science, materials and so forth—except of course, that required to produce the 'green' electricity.

In fact, by and large, most heating and stationary power applications (for example in factories) currently fueled by hydrocarbons could be replaced with electrical equivalents in fairly short order as a result of natural end of life capital investment. We stress that, assuming the electricity were available, this could all be done without the need for new materials like those required for long lived PEM cells, cheaper catalysts (or cheaper platinum), safe, lightweight and compact hydrogen storage systems, a hydrogen generation and distribution infrastructure, and all the science and solutions so earnestly sought by the fuel cell and hydrogen industry at such a cost.

The major weakness in our argument is the simple fact that there is currently no practical way of storing a large quantity of electrical power, and conditions are not always favourable for the generation of power by solar panels or windmills. This is a valid point, and one that defies easy resolution. Indeed, generating hydrogen using excess electrical power during low demand periods for storage and use during high demand periods may be a valid and effective application of industrial scale phosphoric acid, molten carbonate, or solid oxide fuel cells, especially considering the high cogeneration efficiencies available with such systems.

There are, however, mostly price based schemes that can be used to 'smooth' energy consumption in line with production capacity. For example, a sufficient spread between peak and off-peak pricing can smooth consumption patterns, and it is not beyond the realm of reason that flexible technology such as 'smart' appliances could adjust their operation on the basis of available production capacity. Similarly, a major use of electricity is heat, in particular heating water. One could readily conceive of a system whereby homes have an additional highly insulated large hot water tank that would superheat water when prices are low and meter out moderately heated water for domestic or heating use as required.

To be pedantic about it, generation of hydrogen would then only make sense if the efficiency of the fuel cell was so efficient as to economically justify the investment in the development and production of the fuel cell, hydrogen storage and production technologies, the requisite infrastructure for producing cells, generating, storing and transporting hydrogen, and so on and so forth, after taking into account the often sizeable energy and financial costs associated with these activities. Investment in a hydrogen economy could be counter productive unless this was all known with a high degree of certainty, in advance.

Technological and Infrastructure Challenges

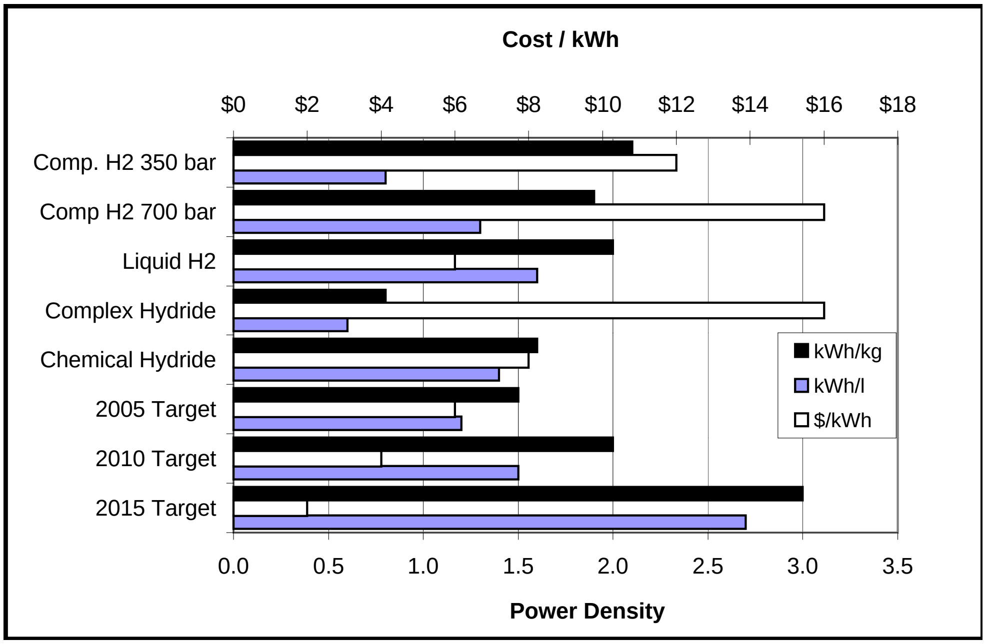
Besides the direct challenges faced by fuel cell developers, the transition to a hydrogen economy requires solutions to a number of technological challenges as well as the construction of a complete new infrastructure.

Hydrogen is the perfect fuel: it is incredibly abundant, has relatively high energy per unit weight, and burns to produce water as a waste product. All of this is true, but it leaves out many details.

For example, while hydrogen is the most abundant element in the universe, it is not found on this planet except in combination with other elements. Any free hydrogen available on the planet has either drifted off into space or made into water and other compounds. In general, producing hydrogen gas requires the input of energy in one form or another. For example, it is relatively straightforward to break water into hydrogen and oxygen by passing an electric current through it. In this case, the energy input is in terms of electrical power, which is always more than the energy value of the hydrogen produced. Similarly, the energy value of hydrogen produced from hydrocarbons such as natural gas is always less than that of the natural gas and whatever other inputs go into the process.

Another issue is that, while hydrogen's energy value per unit weight is quite high, because it

Chart 6: *Hydrogen Storage Systems vs DOE Objectives*



Note: Only liquid H2 meets DOE 2005 objectives and none currently meets 2010 objectives
Source: http://www.eere.energy.gov/hydrogenandfuelcells/hydrogen/storage.html and BMO Nesbitt Burns

is a gas its energy content per unit volume is rather modest, which means that it must either be highly compressed or liquefied in order to be a practical fuel for mobile applications. Both compression and liquefaction are energy intensive processes, which effectively reduces the efficiency of hydrogen in such applications. Furthermore, because the density (weight per unit volume) of liquid hydrogen is so low (roughly on par with Styrofoam), the space required to provide reasonable range is quite large.

For example, to provide the 480 kilometre (300 mile) range considered the minimum required for commercial viability, would require roughly 5 kg, or just under 80 litres (about 21 U.S. gallons), of liquid hydrogen. For comparison purposes, this is roughly the fuel tank capacity of an SUV or minivan: the typical sub-compact automobile has a 45 litre fuel tank. The size of the fuel tank is not a minor issue if one also takes into account that a liquid hydrogen tank must be very strong and heavily insulated, and therefore the outside dimensions of an 80 litre tank would certainly be significantly greater than that in a gasoline powered vehicle of similar size.

Finally, while it is also true that the use of hydrogen in a fuel cell or via burning leaves only has water as a waste product, this is only the case if the hydrogen is produced from a ‘clean’ source. For example, most discussions of the economic viability of the use hydrogen in transportation assumes that, for the foreseeable future, hydrogen will be produced from fossil hydrocarbons, in particular natural gas, through a process known as steam reformation. While burning natural gas results in carbon dioxide, water, and the various byproducts of whatever impurities are present in the gas, steam reforming produces only carbon dioxide and the impurities as byproducts, although energy is consumed in the process. In effect, when fossil hydrocarbons are used as a source of hydrogen, both carbon dioxide and water are produced, more or less in the same amounts as released when burning the hydrocarbons, just in different locations.

Hydrogen Production

As noted above, hydrogen does not exist in any significant quantities on Earth except in combination with other elements. The most likely sources of hydrogen for fuel cells is hydrocarbons, typically natural gas although most fossil fuels would do, and water, where hydrogen can be produced in a relatively straightforward manner through electrolysis.

Hydrogen Production by Steam Reformation

According to the U.S. Department of Energy (DOE), most of the hydrogen in the United States, and about half of the world's hydrogen supply, is produced through the steam reforming of natural gas. Steam reforming is a catalytic process under high heat and pressure that produces a mixture of hydrogen, carbon monoxide, carbon dioxide and other byproducts. The DOE claims that currently, the efficiency of steam reforming reaches the range of 70% to 80%, meaning that 20% to 30% of the energy that goes in to the process is lost, although other sources cite efficiencies of up to 90%.

While steam reformation of natural gas, which mostly consists of methane (CH_4), is relatively straightforward, it is also possible to produce hydrogen in a similar fashion from virtually any fossil fuel, including coal. This has led a number of researchers to investigate the possibility of converting a liquid fuel such as gasoline, into hydrogen 'on board' a fuel cell vehicle, thus obviating two of the major challenges associated with such vehicles, namely fuel storage and the need for a hydrogen distribution infrastructure. Unfortunately, it appears that the efficiency of on board reformers is unlikely to begin to approach that of industrial facilities, which serves to offset the benefits.

PEM fuel cells are particularly susceptible to even trace impurities, in particular carbon monoxide and sulfur, in the hydrogen fuel. Sulfur is commonly found in fossil fuels and carbon monoxide is a byproduct of steam reformation processes. The sensitivity of PEM fuel cells to impurities appears to be a technological issue associated with the materials used in the construction of those cells, and not in principle an insurmountable barrier. Nonetheless, for the near term at least, hydrogen produced by steam reformation must be further processed to eliminate these impurities.

One proposed hydrogen production method involves biomass gasification, which is similar to steam reformation of natural gas, except the feedstock is derived from biomass. The advantage to biomass gasification is that it is a 'closed loop' system and therefore does not result in net addition of CO_2 to the atmosphere.

Hydrogen Production by Electrolysis

While steam reformation produces CO_2 and other byproducts such as sulfur and carbon monoxide, electrolysis is as 'clean' as the electricity produced to drive it. As such, most proponents of fuel cells cite this production method as the hydrogen source of choice, envisioning a future where excess production from wind or solar sources is 'banked' in the form of hydrogen for transportation applications. This is a particularly appealing scenario given that wind and solar power are intermittent (the wind isn't always blowing and the sun doesn't shine all day and all night).

While the promise of electrolysis is great, the fact that significant amounts of electricity is needed is an important detail, especially given concerns about the efficiency of the process. While claims of 'near 100% efficiency' are sometimes made, this appears to be the case only when the hydrogen is produced at a very slow rate, or in other words, at a very low current density. According to the Argonne National Laboratory, "… The efficiency of electrolysis (electricity needed to produce hydrogen) is typically about 75–80%," although we have seen figures from 70% and up.

Other Proposed Hydrogen Production Systems

Table 8: *Other Proposed Hydrogen Production Systems*

	Process Temp (C)	Heat-to-Hydrogen Efficiency (%)	Status
Electrolysis*	-	20-25	Commercial
Sulfur-iodine thermochemical cycle	850	45-49	Pre-pilot
Calcium-bromine thermochemical cycle	760	36-40	Pilot plant
Copper-chlorine thermochemical cycle	550	41**	R&D-ANL

* includes inefficiencies caused by conversion of heat to electricity during power generation.
** Energy efficiency calculation based on thermodynamics
Source: www.cmt.anl.gov/science-technology/lowtempthermochemical.shtml, BMONB

Besides the familiar reforming and electrolysis hydrogen production systems, a number of other systems are being developed or researched. These include photoelectrolysis, or the direct conversion of sunlight into hydrogen; photobiological whereby hydrogen is produced as a by-product of the metabolism of naturally occurring or genetically engineered organisms; and thermochemical cycles, whereby a sequence of chemical reactions effectively splits water into hydrogen and oxygen through the application of heat and without the use of electricity, thus saving the inherent losses associated with generating electricity from heat.

What these thermochemical systems have in common is that they produce hydrogen directly from a heat source. Because the first step in many electrolysis operations is conversion of heat to electricity, which is relatively inefficient, thermochemical cycling can be a more efficient process than electrolysis, depending on the source of electricity. In particular, if a ready source of heat is available for example through geothermal sources, or as we have seen, from a nuclear plant, hydrogen can be produced.

General Atomics believes it can produce hydrogen at about half the cost of electrolysis (depending on capital cost assumptions) using a closed loop using a modern nuclear reactor driving a Sulfur-iodine thermochemical cycle. While nuclear reactor design has come a long way since Chernobyl, we doubt a nuclear option is what environmentalists envision when they consider merits of the hydrogen economy.

Hydrogen Storage

The production of hydrogen can be more or less efficient depending upon the technology used but this is not the end of the story; transportation applications require the storage of hydrogen on board the vehicle.

Hydrogen is a gas at room temperature, and this has significant implications when considering its use as a fuel. To review high school chemistry, one mole of hydrogen (H_2), weighs around 2 grams and occupies 22.4 liters at atmospheric pressure, the volume of a cube around 28.2 cm, or 11.1" on a side. This is roughly the amount of hydrogen gas it would take to propel a fuel cell vehicle 192 metres, or around twice the length of a football field.

To accommodate the range of 480 km expected of a commercially successful automobile, around 5 kg, or 2,500 times as much hydrogen would be required, a volume equivalent to around 56 cubic metres, or about five times the size of a large automobile. Therefore, the volume of hydrogen gas must be reduced for practical mobile applications. The easiest way of doing this is by compressing or liquefying the gas for storage.

Compressed Hydrogen Gas

The compression of a gas costs energy, and the more gas to be compressed the more energy it takes. An industrial scale plant, capable of compressing 1,000 kg per hour to about 200 atmospheres (about 3,000 psi) would be expected to consume about 8% of the energy value of the hydrogen so compressed. The figure rises to around 12% to compress the gas to 800 atmospheres (over 11,000 psi), which is roughly the pressure required to reduce the volume of gas required for an acceptable range to around 80 litres, not including the tank itself.

It is worth repeating that the efficiency figures are for an industrial scale operation capable of compressing enough gas for 200 automobiles an hour. Smaller operations would likely be significantly less efficient, and the vision of ‘at home refueling’ suggested by some commentators would probably use up a significant amount of energy simply pressurizing the gas for use in a vehicle.

A great deal can be said about the safety of hydrogen in comparison with other fuels. We are not excessively concerned with arguments concerning the flammability of hydrogen, given the demonstrable dangers of driving around with a tank of gasoline. At least hydrogen rapidly dissipates when allowed to escape. Nevertheless, we feel it is worth noting that any vessel pressurized to 3,000 psi, let alone 11,000 would present a formidable danger if it ever ruptured. We believe pressure tanks for compressed hydrogen would have to be very carefully designed, and regularly inspected for weakness, as are industrial gas cylinders. While not an insurmountable obstacle, this alone could add significantly to the cost of ownership of a fuel cell vehicle.

Liquid Hydrogen

As a gas is compressed, its boiling point (or the point at which it becomes a liquid) rises until such a point where the compressed gas becomes a liquid. Liquids cannot be further compressed. This sets a lower bound on the volume a certain amount of material can occupy under real world conditions (black holes excepted). Therefore, liquid hydrogen represents the most compact means of transporting elemental hydrogen.

Some gases, such as propane, can be readily liquefied under modest pressure and temperature. For example propane transitions from gas to liquid at around -42°C at atmospheric pressure, and is readily transported as a liquid at higher temperatures if kept under less than 10 atmospheres of pressure. Methane (natural gas), becomes a liquid below around -162°C, while hydrogen liquefies at -252.7°C, or 20 degrees above absolute zero.

This is very cold indeed and requires an insulated container for storage. Although liquefied gas can be stored at ambient pressures, the gas produced as the liquid is warmed must be drawn off or the pressure will increase to the point where the vessel may rupture. Because the boiling point of hydrogen is so low, we believe that a suitable container would have to be very strong as well as very well insulated. This would likely require a sizeable vessel to contain the 5 kg or so of hydrogen needed to provide a suitable range. This amount of liquid hydrogen alone would occupy around 80 litres (roughly the size of the fuel tank of a light truck). We believe a tank capable of storing this amount of liquid hydrogen would have to be considerably larger.

Of course, an alternative to a heavily insulated, super-strong container would be to install pressure relief systems to ensure that pressures do not build to dangerous levels. While a small amount of gas could be stored temporarily, in the event the vehicle was left for any period of time, excess gas would be lost by venting to the atmosphere.

As would be the case with the compressed gas, the hazards associated with a ruptured liquid hydrogen tank would be considerable, although likely more associated with cryogenic dangers than explosion. Therefore, we believe the tank and associated systems would also have to be carefully designed and regularly inspected.

As is the case with compression, liquefaction of hydrogen is very costly in terms of energy consumption. In fact, small plants producing 1 kg, or 8 litres, of liquid hydrogen per hour would probably use more energy in the liquefaction process than that present in the resulting fuel, or yield less than 50% efficiency. Large industrial scale plants are expected to consume roughly 40% as much energy as in the resulting fuel, yielding less than 72% efficiency (1/1.4).

Metal Hydrides

Powders of certain metal alloys, under certain conditions, form relatively loose chemical bonds with hydrogen, permitting them to act as ‘sponges’ for the gas. In theory, these metal hydrides appear to be the idea storage medium for hydrogen as they permit the storage of relatively large volumes of gas in a relatively small volume and yet at comparatively modest pressures (30% atmospheres or 435 psi), and with relatively good energy efficiency. For example, certain metal hydrides store 80% or so hydrogen in the same volume as liquid hydrogen without the associated challenges of ultra-cold temperatures.

Unfortunately, most metal hydrides are rather dense, and the weight of hydrogen stored is only 2% of the weight of the metal hydride. Therefore, while a metal hydride storage system capable of carrying 5 kg of hydrogen would only occupy around 90 litres, it would weigh around 575 kg (over 1,200 pounds) not counting the pressure tank.

Hydrides based on alkali metals have considerably better energy densities, and can deliver about 5% of the combined weight of reactants in hydrogen. In other words, 5 kg of hydrogen could be produced from just under 100 kg of alkali hydride and water, which is a weight not much different from that of a full fuel tank of gasoline in a small truck. Unfortunately, the process of storing hydrogen in alkali hydrides is not very energy efficient. The process requires around 60% more energy than that which can be extracted from the resultant hydrides.

While the efficiency of alkali hydrides storage appears to be less than that for compressed or liquid hydrogen, this may be offset by the relatively simple storage systems required to hold the product, and the inherent losses associated with storing cryogenic or compressed hydrogen. Some schemes for using alkali hydride storage propose refueling by simply loading a new set of fuel canisters, which are transported back to the manufacturers for recharging. The change out process, which could be automated, would probably speed the refuelling process considerably, and is one of the main drawbacks to gaseous storage.

Onboard Reforming

One proposal for delivering hydrogen to fuel cells is simply to convert hydrogen rich fuels such as hydrocarbons into hydrogen through an onboard reforming system. The advantage to this approach is that, especially in the case of liquid fuels, many of the onboard storage issues are greatly simplified as a simple fuel tank would do the trick. In fact, even dealing with gaseous hydrocarbon fuels such as propane and methane is easier than dealing with hydrogen. Another added benefit is that required fuel distribution infrastructure is simpler than with hydrogen, and in many cases, most obviously if gasoline is used as the fuel, may already be available.

There are two major issues with onboard reforming, namely the inefficiency of the process and the need to remove impurities from the resulting hydrogen. Of the two, the problem of inefficiency is the most daunting.

As noted above, the most common (and presumably most efficient) industrial scale reforming systems lose 20% to 30% of the energy of input fuels according to the U.S. Department of Energy (DOE), although some sources cite efficiencies of 90%, or losses of 10%. These loses occur because (fortunately) hydrocarbons do not spontaneously decompose into their constituent elements, even in the presence of catalysts—in general, certain conditions, most significantly high temperatures, must be present in order for this to occur and a loss of energy through heat is inevitable.

We have been unable to find a detailed exploration of efficiency issues associated with onboard reforming, although we can see with a high degree of confidence that a small, onboard reforming system is unlikely to ever approach the levels of efficiency of large scale industrial plants.

One other challenge associated with onboard reforming is the removable of impurities, including those present in the original fuel (such as sulfur), and those produced as a side effect of the reforming process itself (such as carbon monoxide). The most likely means of ensuring that contaminants such as sulfur are not present in the hydrogen produced by the reformer is to remove it from the fuel. It is worth noting that this implies, for example, ‘fuel cell grade’ gasoline or natural gas would have to be a specialty product, unless removal is also done onboard, which is also likely to be less efficient than an industrial plant and likely require regular maintenance. The need for ‘fuel cell grade’ fuel would likely necessitate significant additional capital investment, even to a pre-existing distribution system.

Obviously, the removal of the contaminant byproducts of reforming can only be done onboard if the reformer is onboard. Again we suspect that this it is inherently easier to do on an industrial scale. Nonetheless, we view this as a technical challenge that has the potential to be solved and not an obstacle to the adoption of onboard reforming.

The likely lower efficiency, as well as the added costs of an onboard reformer, including maintenance costs as well as the energy costs associated with hauling the device around, serve to offset the attractiveness of this alternative. Nonetheless, this may be an attractive option, especially during the transition period to a hydrogen economy—a period in which both fuel cell and conventional internal combustion engines remain in use.

Distribution of Hydrogen

The distribution of hydrogen gas to fueling sites is an important consideration for many applications of fuel cells. This is less of an issue if an onboard reforming scheme is implemented, depending on the input fuel requirements for such a system, or in the case of a metal (including alkali) hydride fuel system. Fueling centres that produce their own hydrogen from natural gas or electricity can simply exploit the pre-existing infrastructure for these inputs.

Distribution of Gaseous Hydrogen

On the surface, the distribution of hydrogen gas sounds as straightforward as the distribution of natural gas, and therefore a pipeline similar to that used in natural gas could be employed. As it happens, hydrogen reacts with common seals and lubricants currently used in natural gas pipelines and it will be necessary to develop new materials that will not degrade, nor contaminate the gas on its journey. Furthermore, due to the much lower density of hydrogen, much more of the gas must be moved through a pipe to deliver a certain amount of energy than natural gas. This means the gas must either be moved at a greater speed, or the pipe must be of greater diametre.

It is hard to imagine that an extensive hydrogen distribution pipeline will be built unless hydrogen becomes an alternative to both gasoline in vehicles and natural gas in home use. Absent a pipeline, it will be necessary to truck hydrogen to distribution centres in the same way that gasoline or propane is currently delivered.

As noted on page 31, the lower density of hydrogen necessitates significant compression in order to pack a suitable amount of energy into a relatively small space. This is an energy intensive process with important ramifications for hydrogen distribution because it determines how much hydrogen can be delivered with a given vehicle, and the effort required to transfer the gas into onsite storage, or at least into a vehicle.

Bulk compressed gas is currently transported in ‘tube trailers’. While the trucks have much greater weight hauling capacity, the volume of pressurized gas they can handle is limited by the physical size of the trailer. A common trailer design seems to be able to carry roughly 21 cubic metres of gas at currently used pressure levels of 200 atmospheres, which works out to around 320 kg of gas. This is enough hydrogen to refuel only 72 vehicles at 5 kg each so a refueling station would likely require several deliveries a day so as not to run out of fuel.

Gas is currently transported at significantly lower pressure than that required to reduce the 5 kg of hydrogen needed to provide a reasonable range to a fuel cell car into a small enough volume (80 litres) to fit in that vehicle car. If the tube-trailers could be redesigned to deliver gas at this pressure (about 800 atmospheres) each would carry around 1,280 kg of gas, or enough to refuel 284 vehicles. While the number of vehicles served by a filling station varies widely, we note that the station in our rural area serves, on average, approximately 200 vehicles per day (although admittedly not all these are 'fill ups'). It is reasonable to assume that stations in more populous areas would serve a multiple of this number of vehicles every day. We believe that the limited gas carrying capacity of tube trailers is suggestive that many service stations would still require multiple deliveries each day.

It is worth noting that these tankers are quite heavy, despite their modest hydrogen fuel delivery capacity. Therefore, there is a comparatively high energy cost associated with such deliveries. Furthermore, if one considers the required frequency of deliveries, depending on the distance between the hydrogen production facility and the fueling station one can easily imagine a situation whereby each station would have to have a truck and driver employed full time just for the delivery of fuel to the station. This does not appear to be a cost effective option. Finally, while compressed gas delivery by truck is not uncommon, this option would greatly increase the number of trucks on the road loaded with this dangerous cargo and this could cause safety concerns.

Distribution of Liquid Hydrogen

As is the case of gaseous hydrogen, liquid hydrogen could be delivered via pipeline or truck. Unfortunately, given the fact that liquid hydrogen must be kept very cold, we doubt pipeline delivery of hydrogen is practical over any distance, even setting aside the energy costs of maintaining a low temperature.

It seems likely to us that liquid hydrogen would probably be delivered to filling stations by truck. Because liquid hydrogen is not necessarily transported under pressure, tube trailers are not required and the volume of fuel that can be transported is much greater than what is possible with the compressed gas. Nonetheless, as noted above, the density of liquid hydrogen is very low, and the tanker would have to be heavily insulated, so only around 2,000 to 4,000 kg could be delivered by a single tanker, enough to fill 400 to 800 vehicles, or a two to four day supply for rural fueling station, yet only a 5 to 10 hour supply for a station on a busy highway.

While the refrigeration costs of storing liquid hydrogen have the potential to be daunting, the relatively short periods the product would be stored at a fueling station probably mitigates this considerably. Furthermore, many liquid gases, such as Liquefied Natural Gas (LNG) effectively self cool by boiling off, with the vapor put to good use as fuel. For example, a fueling station, or transport truck could be fueled by the hydrogen gas produced as the liquid boiled. Unfortunately, this is not a viable solution for a parked vehicle as the gas would have to be vented to the atmosphere (at considerable cost of wasted fuel) or tremendous pressure would build up in the tank.

On Site Hydrogen Production

On site production of hydrogen is effectively a distribution system whether based on locally performed electrolysis or steam reforming. However, small scale hydrogen generation systems are not particularly efficient, especially with respect to compression or liquefaction, and something over one-third the amount of energy used in refueling would be lost as a result, depending on the capacity of the facility.

As a result, we doubt on-site production is a viable solution to hydrogen distribution for transportation applications, except for demonstration purposes.

Distribution of Metal Hydrides

Despite the exotic chemistry involved, metal hydrides appear to present a relatively simple distribution challenge. The model envisaged is to distribute standardized cartridges of preloaded metal hydride.

If made from alkalis, a ‘fill up’ would be roughly the same size and weight of current fuel tanks, so distribution of cartridges could be accomplished with a truck the size of a regular fuel tanker. For example, a truck would arrive with a full trailer of cartridges and exchange it for a full trailer of empty cartridges, which would be then be returned to a recharging site. The process of switching trailers would probably take less time than is currently used to pump fuel from a tanker into a ground tank.

Therefore, while production facilities and transportation networks for metal hydride cartridges do not currently exist, it seems like a rather straightforward problem to solve. In fact, while automated cartridge handling systems (where a vehicle would have depleted cells swapped for recharged ones) may sound complex, such a system would probably be relatively simple to design.

Onboard Reforming

As mentioned above, onboard reforming can use input fuels such as natural gas, gasoline, and methanol and the distribution systems for these fuels can be much simpler than those for the distribution of gaseous or liquid hydrogen.

If gasoline were used as the input for an onboard reformer, existing gasoline refueling centres could simply offer extra pure gasoline as another grade of fuel, much like high octane is sold today. Because a consumer methanol distribution system does not currently exist, methanol distribution is more complex, as special tanks and pumps (as well as delivery vehicles) would be required. Fortunately, these would be similar to those required for gasoline, and likely involve similar costs.

In principal, a natural gas refueling centre could be connected to an existing pipeline and simply consist of a number of ‘pumps’ to pressurize the natural gas into the vehicle’s tank. In practice, however, natural gas impurities are best removed at the refueling point and this would add to cost. It should be noted that filling a tank with pressurized natural gas would likely be time consuming and costly from an energy perspective.

The Challenge of Refueling

Part of the challenge of distributing fuel to drivers is getting the fuel from one repository to another. For example, filling a tube trailer with compressed gas at the production centre, transferring it to the vehicle (the transfer from the tanker to the fueling station is unnecessary if the truck simply exchanges an empty trailer with a full one).

This is not usually the sort of challenge that gives one pause because the transportation fuels in use today are all liquids, and gravity or a pump can be used to rapidly transfer a liquid from one vessel to another. However, since pressurized gas moves from a high pressure to a lower pressure, one would think that moving it around would be straightforward and quick as it flows from source to destination, except that the source pressure begins to drop and the destination pressure begins to rise, the instant the transfer begins. Therefore, the rate of transfer begins to slow immediately and the overall pressure drops throughout the process.

Therefore, refueling requires powerful high pressure compressors to achieve the storage pressures needed to carry enough hydrogen to provide an acceptable range for a vehicle. Even then, it may take some time to complete a fill up.

Of course, the use of liquid hydrogen simplifies the process of refueling as it is just another liquid to be pumped into a vessel. Nonetheless, the safety challenges associated with dispensing a cryogenic liquid should not be underestimated.

The simplest, safest and likely quickest refueling schemes would be when the hydrogen is produced by onboard reforming of a liquid such as methanol, or when metal hydride canisters would be used as these could be quickly swapped out for fresh ones, potentially through an automated system.

Conclusion

Many scientists and transportation industry experts believe the energy source of choice in the future will be hydrogen, and that PEM fuel cells will supply electricity to such applications as transportation in this hydrogen based economy. If this is to be the case, many obstacles will have to be overcome including technological ones such as developing cost effective, reliable and durable fuel cell technologies as well as other challenges such as the construction of a complete hydrogen production and distribution network. It is important to realize that these challenges do not exist in isolation, but within a multidimensional context whereby innovations such as hybrid gasoline- or diesel-electric vehicles, more efficient engines and/or light weight auto design interact with factors ranging from the relative costs of fuels, public policy with respect to mass transit, urban planning, and the cost of capital.

Although optimism for the hydrogen economy is virtually universal, we believe and respectfully submit that it is improbable hydrogen will become a major fuel source within the next 25 years, or even, potentially, this century. This is not because we believe the various obstacles will not be overcome, but that we believe because hydrogen is an energy carrier, and not an energy source, whatever energy sources may be exploited in the future could be put to more effective use directly, without significant involvement of hydrogen or fuel cell technology general. Such progress would, in turn, reduce the demand for fossil fuels and mitigate the environmental impact of widespread use of such fuels for non-transportation applications.

Although we are confident of our conclusions, we recognize that our views are often at odds with consensus, at least over the near term. Therefore, speculative investments in fuel cell and hydrogen economy related companies may actually produce capital gains for investors as a result of near-term excitement over technological (or even political) developments, or as a result of consolidation. Nonetheless, we believe that it is unlikely such companies will produce sustained free cash flow, and therefore a reasonable return from an economic perspective.

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