Future Fuels

F. David Doty, PhD, david@dotynmr.com, Feb. 2004. Updated Mar. 2006

Doty Scientific, Inc., Columbia, SC

Introduction: Few now doubt that we are rapidly approaching two conflicting mega-challenges – Peak Oil, and major climate change. If, in our response, we ignore the economic and social lessons of the past forty years from other dream solutions, such as fission, fusion, and orbiting microwave power stations, the consequences will likely be disastrous. The goal of a hydrogen economy was first officially proposed at least 40 years ago by U.S. President Richard Nixon, and some then expected many would be driving hydrogen vehicles within ten years. However, it has becoming increasingly clear over the past several years that hydrogen vehicles will not be practical, and our only viable, long-term option is dramatically increased use of renewables – especially wind, liquid biofuels, and solar – and advanced nuclear concepts.

It was encouraging to see Nobel Laureate George Olah (chemistry, hydrocarbons) recently point out that a "Methanol Economy" seems more practical than a "Hydrogen Economy" [*1*]. He notes that in recent years, very efficient methods of dehydrating bio-methanol into bio-ethylene (C_2H_4) and water have been developed. Ethylene, in turn, can be used to efficiently produce all hydrocarbon fuels and products currently obtained from fossil sources. But this is just one of literally dozens of highly promising biofuel avenues that are just beginning to be explored and developed. Biodiesel, ethanol, bio-gasoline, bio-jet-fuel, and bio-methane can be efficiently and safely produced, stored, and transported within the current infrastructure. Direct Methanol Fuel Cells (DMFC), which convert methanol directly into water and CO_2 while producing electricity, have advanced to the point that they are now beginning to appear in commercial products such as cellular phones, laptop computers, and some military equipment. While there will undoubtedly be some economically viable applications for DMFCs and perhaps some for non-mobile hydrogen fuel cells, as shown in **Figure 1**, economically viable solutions for a number of fuel-cell challenges in automobiles seem highly unlikely within the next half century.

Figure 1. This recent, “light-weight” 2 kW PEMFC system (stacks, compressor, regulators, controller, no storage), at 50 kg, is more massive than a 20-year-old 2 kW diesel gen-set. Its price has increased by 21% to $17,000 during the past year [*2*].

Hydrogen Fuel costs. For the past 40 years, most cities of population over 100,000 in industrialized nations have had dozens of industrial and research users regularly purchasing 14 MPa (2000) psi hydrogen gas in heavy steel cylinders containing about 0.6 kg H_2 per cylinder. The price of this hydrogen has been reasonably stable at about $100/kg (about fifty times the cost of gasoline per unit energy), plus cylinder rental. The current cost of a full tanker truck (15,000 gallons, or 4300 kg) of liquid hydrogen (LH2) in most regions in the U.S. for high-volume customers is about $7/kg [*3*]. One of the basic assumptions underlying the putative "hydrogen economy" is that the cost of high-pressure hydrogen gas can be reduced to a few dollars per kilogram for the individual consumer even while the price of natural gas rapidly increases over the next 30 years. There are serious problems with this assumption, as discussed in more detail in a separate article [*4*] and summarized here.

A number of studies have been carried out over the past seven years on the cost of hydrogen, but there are major problems with most of these studies that are not widely appreciated. The four biggest problems with most hydrogen cost projections are:

1. The rate of introduction of hydrogen-fueled vehicles is currently nearly two orders of magnitude lower than was generally expected in the late 1990’s [*5*], and it seems likely to remain at such a depressed rate for at least several more decades [*6*]. This is largely because the cost of moderate-weight proton exchange membrane fuel cell (PEMFC) stacks are still $3000/kW [*7*], which is nearly two orders of magnitude higher than was officially expected in the late '90's [*8*]. Also, their lifetime under road conditions is still 20% that of the diesel engine, and they achieve under 35% efficiency [*7*] while current diesel engines achieve over 40% efficiency [*9*].
2. North America is facing natural gas (NG) shortages that will steadily worsen over the coming decades [*10*]. The U.S. price of NG has increased by a factor of 10 in the past 30 years and more than a factor of three in the last six years [*11*]. Its cost seems likely to increase by another factor of two (in constant dollars) within 10 years in North America.
3. Small hydrogen-dispensing stations (100 kg/day) are costing about $1,050,000 each [*12*], which is ten times more than was initially expected for stations an order of magnitude larger [*13*] and is thus another error in earlier assumptions of two orders of magnitude.
4. Hydrogen storage costs by all methods (at least for quantities below tens of thousands of kilograms) are two orders of magnitude greater than for liquid hydrocarbon fuels [*14*]. This is not appreciated in many published studies which have often referenced erroneous earlier works [*8, 13*].

Other issues which were not well appreciated in earlier studies include (1) the increase in pipeline costs to avoid hydrogen embrittlement failures [*15*], (2) the high, fixed operating costs of hydrogen dispensing stations, and (3) the implications of taxes, including the imposition of a fossil-carbon tax or similar disincentive to the use of fuels such as fossil hydrogen which have huge life-cycle green-house-gas emissions.

All of these errors in prior studies have been in the direction to make hydrogen seem more attractive as a fuel. However, it is important to point out that several thorough and generally accurate infrastructure studies have been carried out [*12, 14, 16*]. But even the rather scholarly works are often misused by hydrogen advocates who fail to carefully note their assumptions:

1. NG costs were usually assumed to be $3.5/GJ – compare to today's $10/GJ at the well head, $12/GJ at the city gate, and probably $25/GJ at the city gate in 2020.
2. Dispensing stations were often assumed to be filling 300 vehicles each per day – about two orders of magnitude more than seems likely for at least 15 years.
3. Often 300,000 hydrogen vehicles were assumed within 100 km of the central station with a total demand of 150 tons/day – three orders of magnitude more vehicles than seems likely for at least another two decades.

It has been suggested that the show-stopper issues of FC-stack cost and reliability can be avoided by using hydrogen-fueled internal combustion engines (ICEs). Indeed, such have been demonstrated and engine efficiencies up to 38% (LHV) may ultimately be possible with better mixture control in lean-burn engines, but current efficiencies are generally in the 22-28% range [*17*] – 70% that of the advanced gasoline engine [*9*]. Moreover, hydrogen ICEs still have all the fuel-cost, fuel-storage, and safety issues of hydrogen FC vehicles [*7*]. As a result, they will never compete with the gasoline or diesel hybrid, so sales will be low and costs will remain high.

Some studies have concluded mini-reformers (if mass produced) at corner filling stations could produce hydrogen at $3.4-4.3/kg for natural gas priced at $5/GJ [*18*]; but other data and experienced-based studies suggest this is a realistic price only from a much larger plant (24 tons/day), and the cost would likely be $13.3/kg from mini-reformers (100 kg/day) at current city-gate gas prices [*12, 19*]. Moreover, local reformation is simply not compatible with CO_2 sequestration, and it would increase dependence on natural gas. Current proved U.S. natural gas reserves will last only 10 years, and there is increasing pessimism about future discoveries [*20*]. Until quite recently, most analysts have predicted sufficient natural gas reserves worldwide for the next 30 to 50 years. However, the most recent, detailed gas resource analysis, published in the Oil and Gas Journal, now predicts global conventional gas production peaking in 2019 [*21*].

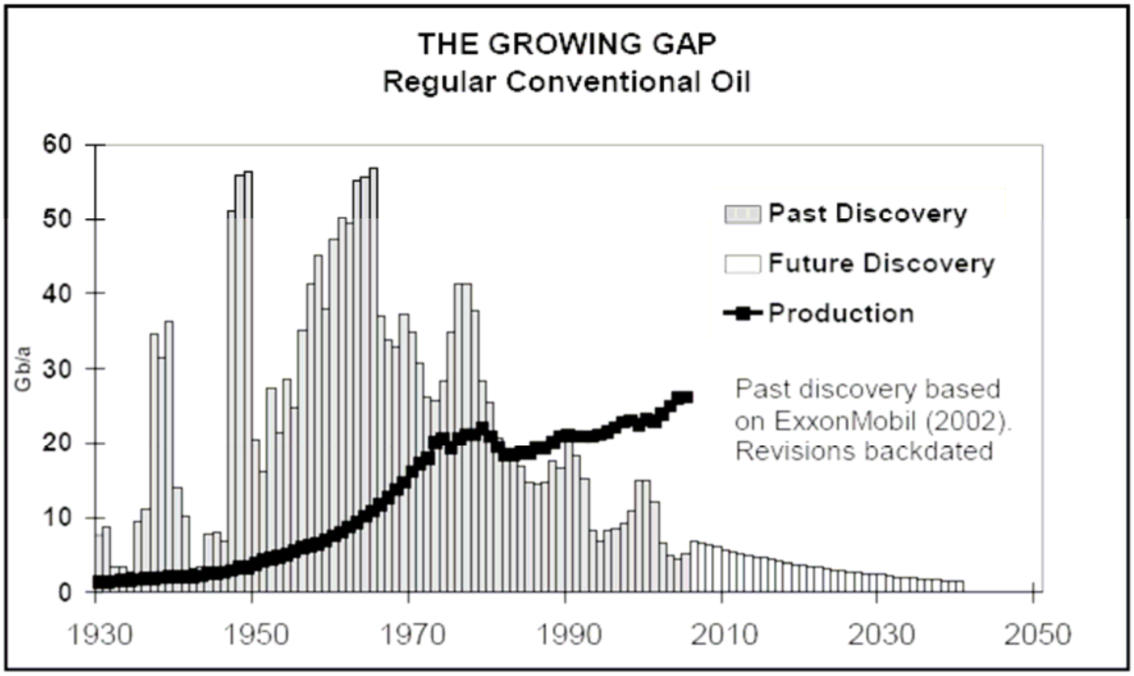
There are, of course, a number of possible sources of hydrogen other than NG – coal, advanced nuclear reactors, wind farms in ideal locations, biomass (pyrolysis and water shift), catalytic reformation of ethanol, hydrogen-producing bacteria (such as various *Clostridium*), and solar electrolysis. Of these, only coal currently begins to compete economically with NG, but generating LH2 from coal produces at least 8 kg of carbon (29 kg of CO_2) per kilogram of H_2 [*7*]. When a realistic future (fossil) carbon tax of $0.1/kg of carbon is included [*22*], coal is likely to remain uncompetitive.

It is worth noting that the DOE/EIA have been forced to make large upward revisions in their price estimates (for gas, oil, and coal) every year for the past nine years. (For example, in 1998, DOE was expecting oil to be $23/bbl in 2005 (in current dollars), when it in fact averaged $57/bbl. Many experts outside the U.S. have done a much better job.) Their latest adjustment was more than a 50% upward revision in the price of oil in 2020. Although there are theoretically abundant stranded NG reserves worldwide for at least the next 40 years, the shortages in North America are becoming critical, as Canada is cutting back on exports (at the rate of at least 2%/year) to preserve their limited domestic resources [*20, 23*]. This is forcing the U.S. to frantically develop the infrastructure needed to import more liquefied NG (LNG) from the Persian Gulf, East Caspian, Northern Africa, South Pacific, Western Siberia, Nigeria, and other places where NG is currently abundant and cheap [*24*]. In 2004 the DOE/EIA nearly quadrupled their projections for 12-years-out of LNG imports while cutting their projections of NG imports from Canada in half [*25*]. Also, numerous downward revisions of gas and oil reserves by various companies have been made during the past two years.

The prices of LNG and fuel oil have stayed fairly close per unit energy for the past two decades (especially for the past seven years), and it is clear that LNG will not drop below fuel oil prices for prolonged periods – a simple fact that the DOE/EIA do not yet appreciate. World-wide oil demand exceeded oil production in the first three quarters of 2005, driving oil prices up strongly. World oil prices (the dominant market) will establish minimum international LNG prices. As carbon taxes begin to be imposed and China's demand for LNG explodes, LNG will consistently exceed pre-tax petroleum prices – probably by at least 25% within 25 years.

The gap between global oil production capacity and global demand dropped from over 8% in 2001 to essentially zero in 2005, and China continues to deal with chronic oil and gas shortages. Many oil experts contend there are good reasons to believe that the Middle East reserves are significantly overstated. The assessment of oil reserves by the Association for Peak Oil [*20*] is now widely recognized (except within the U.S.) as the gold standard in this field. They note that production of conventional (cheap) oil peaked in 2004, and they are predicting (total) Peak Oil to occur in 2010. Campbell's famous graph, "The Growing Gap", reproduced in **Figure 2**, is most telling [*20*]. Although total production growth over the next several years seems likely to be sufficient to limit price growth for several years, it will be a short reprieve. A reasonable estimate is for the price of oil in the U.S. to increase at about 12% annually over the next decade.

The price of oil will trend toward the price of the replacements [*23*]. At energy prices of several years ago (see **Figure 3**), it appeared that advanced biofuels (as discussed shortly) could be produced at around $32/bbl [*26*], but at likely fertilizer and energy costs 15 years from now, $90/bbl (2006 dollars) now seems a more likely cost for advanced biofuels from energy crops.



Limitations in scale-up capacity of replacements seems likely to push the price much higher for 10-20 years. If oil is $120/bbl 8 years from now (in 2006 dollars), imported LNG will be at least $20/GJ (more likely $21/GJ, assuming a modest carbon tax) and NG at the city gate will exceed $23/GJ. (Appreciation of this expectation has caused Iran to delay its LNG developments to get more favorable prices four years from now.)

So what can the typical consumer expect to pay (in current dollars) when filling his/her vehicle with pressurized hydrogen from an unsubsidized dispensing station in a mid-sized city not near a gas field? Clearly, previous cost estimates [*5, 7, 14, 16, 19*], that (1) assume 50,000 to 300,000 hydrogen vehicles per city, (2) are based on natural gas prices from 2001, and (3) ignore the huge, demonstrated dispensing-station costs, are of very little value.

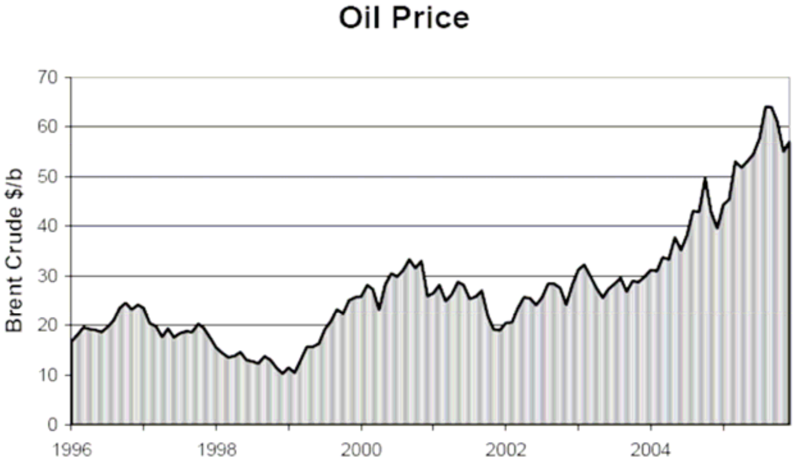


Figure 3. Price per barrel of Brent crude oil, 1/1996-12/2005.

As earlier noted, as recently as 2000 some well-placed "experts" (at DOE and elsewhere) were expecting there would be 10,000 fuel cell vehicles (FCVs) on the road today [*5*]. Most experts today are expecting fewer than 1000 will be on the road five years from now. Some think the numbers will grow much more rapidly in the following decades, though there is really no economic basis to support such projections. But let's be optimistic and assume there are 100,000 hydrogen vehicles on the road in 2015 – divided amongst the 100 cities of population over one-half million in the industrialized nations throughout the world. **Figure 4** summarizes projected fuel cost components for several different scenarios. For example, in case 3, assuming 1000 hydrogen vehicles per large city in the year 2015, consumers could expect to pay $19/kg for hydrogen. Note it is the huge dispensing costs associated with hydrogen when the number of vehicles per city is under 4000 that have previously been most often ignored, but available historical data support the estimates here [*4, 12*]. The other component that will surprise many is the reforming cost, as most prior estimates have assumed a plant producing several hundred tonnes of H_2 per day, even though such a plant would be too large except for the largest cities with over 50% of the vehicles using hydrogen. The methods and assumptions for these projections have been laid out in more detail elsewhere [*4, 12*]. Even these assumptions now seem quite optimistic – especially the LNG cost projections and numbers of FCVs per city.

The current U.S. pre-tax cost of diesel, on the other hand, for the individual consumer at the local station is about $0.7/kg. Of course, one needs 3 kg to equal the energy of 1.0 kg of H_2, but that still leaves an order of magnitude cost advantage for diesel per unit energy. Estimates suggest the pre-tax price of bio-diesel from either bio-methanol or several oil-seed crops could stay below $1.5/kg in the U.S. We return to this subject in a little more detail later.

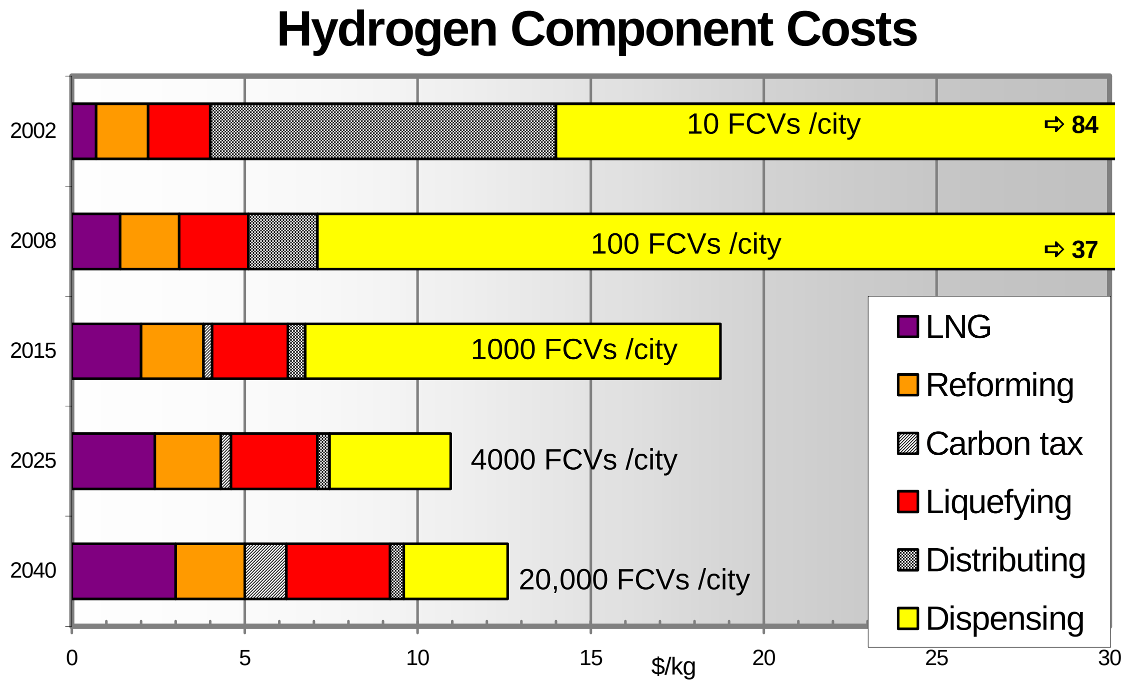


Figure 4. Unsubsidized hydrogen cost breakdown for several years and numbers of FCVs per city. Assumptions, notes: All costs in 2005 USD/kg of H_2. “LNG” is cost of imported liquefied natural gas, distributed to city, with energy equivalent to 1 kg H_2. “Reforming” includes additional LNG and equipment costs. Additional local demand present to utilize all LH2 from a plant producing 22 tons/day. Power costs inflating 1.5%/ year. Tanker truck distribution. 5000 psi dispensing station.

We are well aware of the sharp discrepancies between our projections and earlier projections by all others. However, it is gratifying to see that several other leading hydrogen researchers have revised their cost projections within the past year to be essentially in line with ours [*12*]. We caution that no one should attempt to make any energy-related projections without reading Chapter 3 of Vaclav Smil’s “Energy at the Cross-roads”, in which he discusses hundreds of failed energy projections over the past thirty years [*27*]. A key lesson there is to appreciate historical data. Interestingly, his more recent writings seem to not fully appreciate the economic lessons and steadily improving geological data of the past three years.

It should also be noted that global, recoverable, coal reserves are more limited than previously thought, so even coal is a relatively short-term option, especially if also used to meet oil and gas deficits and to produce LH2 with carbon sequestration, where net efficiency is under 48%.

Fuel-cell engine costs and performance. Phosphoric-acid, carbonate, and alkaline fuel cells, all of which are an order of magnitude easier to produce than PEMFCs, are available at prices under $3500/kW, but they are far too massive for use in automobiles [*7*]. The only type of hydrogen fuel cell being pursued for automotive applications is the PEMFC, also called PEFC (polymer electrolyte fuel cell). The cost of PEMFC vehicle engines (fuel cells, power conditioning, electric motors, etc.) is often reported to be in the range of $3,000-8,000 per kilowatt (100 times that of the common diesel engine), but available data suggest otherwise.

Inspection of the sales and financial data over the past two years from the largest current producer of PEMFCs for non-mobile use (Plug Power) suggests costs of 5 kW PEMFC-based AC power sources (not including R&D) are actually in the range of $15,000-$30,000/kW [*28*]. Larger PEMFCs with 30-35% HHV (higher heating value) electrical efficiency may be available in the range of $3000-5500/kW for combined heat and power (CHP) applications [*7*], but these FCs have inadequate environmental and vibrational tolerance for vehicles, in addition to being much too large and massive. (UTC secured DOE funding by proposing to make CHP PEMFCs available for $1500/kW. They apparently delivered some 75 kW demo units, partially subsidized by EPRI, for $2600/kW, that are getting 31% efficiency [*7*].)

Over the past ten years, Ballard Power has probably furnished nearly 80% of all vehicle fuel-cell engines world wide. By some methods, one could conclude that the manufacturing cost, not including true R&D, of their latest fuel-cell engines (which still don't work reliably over an acceptable range of climates) has been over $1M each [*29, 30*]. Honda estimates the cost of their fuel-cell car will be $100K in mass production, which is expected to begin in 2012; and Toyota is projecting they'll be selling an FCV for $50,000 in 2015. Similar cost projections in the fuel-cell industry for the past decade have proven overly optimistic by factors of 3 to 8. It is noteworthy that fuel cells, including polymer types, have been in use and development for over forty years, and costs have not yet begun to drop significantly – notwithstanding many assertions to the contrary that use artificial costs from heavily subsidized projects or cite costs of massive, stationary fuel cells that are unsuitable for vehicles.

The cost of the PEMFC has relatively little dependence on the cost of the platinum catalysts. Its cost is mostly in the manufacturing complexities, and there are a number of fundamental reasons why the manufacturing problems of PEMFCs have not yielded to the hundreds of millions of dollars of R&D directed at them over the past decade. The simple concept figures often shown of two cross-flowing streams, hydrogen and oxygen, separated by a magical membrane, belie the serious challenges in a vehicle-grade PEMFC. **Figure 5**, taken from the DOE Fuel-Cell Handbook [*31*], does a little better job by showing that at least three isolated adjacent streams are required; as without the coolant stream, both water and thermal management are impossible. Miniaturization results in rapidly increasing pressure and electrical resistance losses. The limited dimensional stability of membrane materials contributes to flow separation and reliability issues. One of the big challenges is keeping just the right amount of moisture present in the membrane for good efficiency as temperature, load, and flow rates change.

A cost discussion is not complete without a discussion of reliability and lifetime. Some PEMFCs have reportedly demonstrated lifetimes compatible with driving more than 100,000 miles, but lab tests and road tests are very different. (We're still waiting to see a fuel-cell vehicle driven from Miami to Maine via the Smoky Mountains in the winter. Then, we need to see one hold up to a

40-minute daily commute for more than two years with minimal maintenance, and come through a highway accident with less than $200K in damages.) Fuel-cell-stack lifetimes under environmentally limited road conditions are still typically 15-25% those of conventional diesel engines, partially because trace amounts (below several ppm) of H_2S, SO_2, NO_2, NH_3, CO and other contaminants in the atmosphere or fuel can temporarily or permanently incapacitate a PEMFC. When lifetime and maintenance are considered, one can argue that vehicle-qualified PEMFCs, which are still not competitive on a power per mass basis, are currently 400 times more expensive than diesel engines.

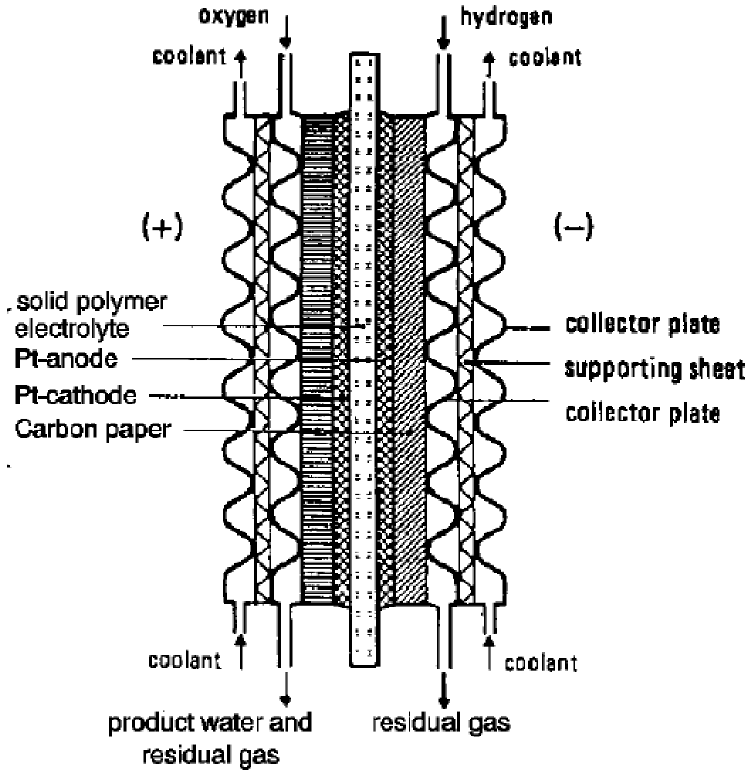


Figure 5. Simplified PEMFC schematic.

Finally, it is necessary to look objectively at efficiency. Yes, it is possible to exceed 65% efficiency in a very expensive and very massive solid oxide fuel cell (SOFC) at very high temperatures under moderate loads, but economic factors will dictate the use of low-cost PEMFCs, operating only a fraction of the time at optimum load, so mean stack efficiency is likely to be under 38% [*7*]. The power electronics needed to regulate the battery charging and drive the motors could achieve 97% efficiency, but in the real world, 92% is more likely. The motors could achieve 96% efficiency, but 86% is a more likely typical number, for both cost and mass reasons. So net highway tank-to-wheels efficiency is likely to be under 32% in a production FCV. Moreover, the idle power consumption of an FCV is around 3 kW, while the idle power consumption of a hybrid vehicle is usually under 1 kW. It is also useful to note that the vendor of the state-of-the-art 2 kW PEMFC shown earlier in Figure 1 does not publish an efficiency. Rather, its volumetric hydrogen consumption rate, 25.2 L/min, is published, from which one initially calculates an HHV efficiency of about 41% at 2 kW, assuming the hydrogen at atmospheric pressure – until noticing that the minimum allowable inlet pressure is 130 kPa. So apparently its HHV efficiency at rated power is only 31.5%, comparable to that of an advanced diesel gen-set of similar size.

Gasoline engines have achieved 30% peak efficiency for two decades, and soon they will reach 38% efficiency [*9*]. Diesels have achieved 42% peak efficiency for more than a decade, and soon they will exceed 58% efficiency [*9*]. With variable valve timing, they can achieve high efficiency over a very broad speed range. Either of these ICEs is fully compatible with low-cost renewable fuels that release no fossil CO_2. Advanced diesels with next-generation catalytic converters are clean, quiet, efficient, reliable, and affordable.

Fuel storage mass, volume, and safety. Safety-approved low-cost compressed gas cylinders currently achieve 1.5% H_2 storage by mass at 34 MPa (5000 psi). Aluminum tanks might achieve 6% H_2 storage. Pricing data from the high-volume production of aluminum scuba tanks suggest high-volume production of 5000-10,000 psi tanks for storage of 3-8 kg of H_2 might cost

$600/kg of H_2 [*32*], which is about 30% less than suggested in an earlier study [*14*]. Carbon-fiber-wrapped tanks may have inadequate impact strength for private transportation, and their costs are still high. An $8,000, carbon-fiber-wrapped fuel tank achieving 11% H_2 storage seems impractical for the small private car. The ultra-thin wall of these brittle tanks is not faithfully presented in the manufacturer's promotional pictures, as shown in **Figure 6**.

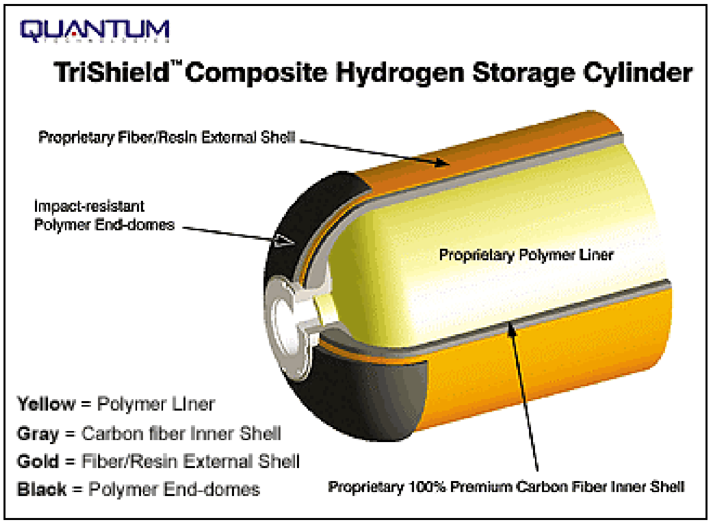


Figure 6. The ultra-thin-wall in a brittle, composite, storage tank is not apparent in promotional pictures.

At 5000 psi, the volumetric energy density of H_2 is only 10% that of diesel. The mechanical energy alone stored in the hydrogen tank may be 5 times that of a 50-calliber anti-aircraft shell. The risks associated with carrying this mechanical bomb around are probably two orders of magnitude greater than we are accustomed to accepting in our gasoline-powered cars today. For safety reasons, the recent NAS/NAE study concluded both high-pressure tanks and cryogenic storage "have little promise of long-term practicality for light-duty vehicles" [*7*].

It is important to point out that leaks are not uncommon in high-pressure systems, especially with hydrogen, partly because of its very low molecular weight. A leak, whether slow or fast, from a hydrogen tank inside a garage can easily lead to an extremely dangerous explosion, owing largely to the combination of its very high flame velocity and extremely low ignition energy – about 0.02 mJ, or less than one-tenth that of methane or gasoline [*30*]. Unfortunately, alternative, safer storage methods (metal hydrides, carbon nanotubes, etc.) have thus far proven even less practical because of serious mass, fill time, and cost issues.

Of course, the energy per unit mass of pure hydrogen is three times that of diesel. So the net practical energy density (MJ/kg) of stored hydrogen, after including some extra structure needed for protection in the event of a collision, may be 20% that of diesel. The huge mass and volume penalties associated with practical H_2 storage seem likely to keep the range of marketable hydrogen-powered automobiles (such as the Honda FCX [*33*]) about 60% that of the diesel hybrid – notwithstanding some very expensive concept demonstrations to the contrary.

Infrastructure Development. Some have estimated that the development of an efficient hydrogen distribution infrastructure would cost only $300B, but those sources have consistently underestimated other "hydrogen economy" costs by huge factors. More careful estimates put the minimum infrastructure cost at $500B [*30*]. Most studies are now concluding the best approach would be based on large, central plants [*7, 16*], but the low energy density of LH2 means this will require an increase of *a factor of twenty* in the number of tanker trucks on our already overcrowded highways.

However, infrastructure is more than just fuel distribution. The average vehicle lifetime is currently about 15 years, but it has been increasing rapidly for the past eight years and could be 20 years within a decade. The cost of replacing 120 million cars and trucks over a shortened time frame at even a $70K premium per vehicle is comparable to our nation's total national debt, or the total global energy investment over the past two decades! Perhaps more daunting is the thought of revamping our vehicle manufacturing infrastructure (which includes dozens of multibillion-dollar factories, thousands of smaller support factories, and millions of experienced workers) – before we really have a clue as to how it should be done.

We have seen relatively strong investment in fuel cell companies and divisions during the past twelve years – $400M by venture capital firms, $300M from public investments, and much more from private, federal, and corporate sources. Dozens of fuel-cell-related companies were started over the past decade, but today only a handful of significant players are left in North America: Ballard Power BLDP (PEMs), Plug Power PLUG (PEMs), Hydrogenics HYGS (PEMs), Fuel Cell Energy FCEL (Carbonate FCs), Mechanical Technology MKTY (DMFCs), Distributed Energy Systems Corp (formerly Proton Energy Systems) DESC (PEMs), Astris Energi Inc ASRNF.OB (alkaline FCs), UTC UTX (several types of FCs), and Quantum Fuel Systems QTWW (tanks, H_2 infrastructure). Of these, all except MKTY and UTX are still showing huge losses (MKTY is not showing losses for artificial reasons, and UTX is a large company with other products), and probably only one of the hydrogen PEM fuel-cell companies will be a viable company two years from now. The major auto manufacturers and oil companies have their own fuel-cell projects, but none of them currently appears particularly successful. BLDP and PLUG are currently trading below 4% of their 6-year highs, and a further large drop in valuation seems likely in the coming years. **Figure 7** is typical of many FC firms.

Undoubtedly, if the U.S. DOE invests $2B (as planned) over the next 6 years, a few hundred more demonstration vehicles (at perhaps $400K each) will be on the road, but that won't change much. After all, Ballard, Honda, GM, and Plug Power have each invested over $350M into PEM fuel cells over the past six years (and many other companies and research labs have invested lesser amounts over the past 40 years) with limited progress in manufacturing cost reduction. Notwithstanding recent announcements to the contrary, probably only two major auto manufacturers (Honda and Toyota) will be producing FC vehicles after the DOE support ends six years from now. And those FCVs will be at a price almost no one will be willing to pay.

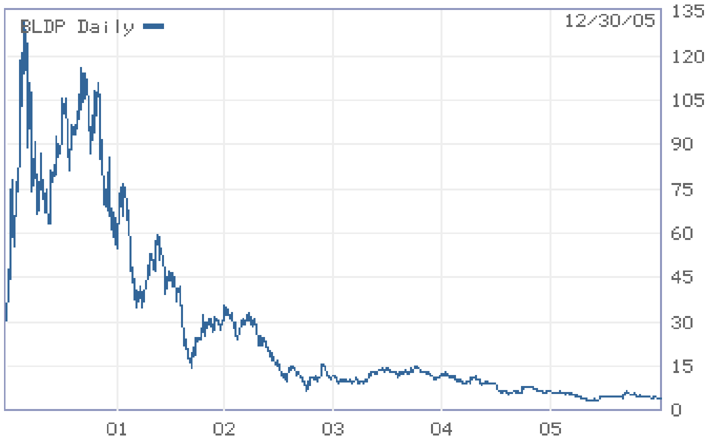


Figure 7. The stock value of the largest producer of vehicle-grade PEMFCs, Ballard Power, failed to respond positively to large cash injections from Ford and DaimlerChrysler on the heels of DOE announcements of major hydrogen research grants.

Global Warming and Fossil CO_2 release. At least 95% of scientists who have looked closely at this issue have accepted human-caused global warming as being real for at least the past several years. The clincher, for the final doubting die-hards, appeared in the June 3, 2005 issue of *Science*, "Earth's Energy Imbalance: Confirmation and Implications", by James Hansen et al [*34*]. This paper is scientifically spellbinding. It is remarkably clear and full of hard data backing up detailed models with amazing agreement. One of the conclusions, based on solid data, is that the mean rate of melting of grounded ice (Greenland, alpine glaciers, West Antarctica ice sheet, etc.) over the past decade has been about seven times the crude estimates generally accepted about six years ago. A key point is that if we don't start taking action fairly soon, because of the inertia built in to the power generation industry (i.e., 40 year lifetime of coal power plants) and the 60-year time constant associated with the response of the climate system to changes in atmospheric CO_2, we could find our planet headed into severe climate change within this century and be unable to avoid catastrophic effects. In fact, the authors note our climate could already be “out of control”. Another recent study has concluded that hydrogen is an indirect green house gas because it interferes with the oxidation of methane via hydroxyl radicals [*35*]. Hence, the expected hydrogen leakage rate from a full hydrogen economy would have a significant contribution to global warming. However, the release of CO_2 during the production of hydrogen is a far greater concern.

The primary source of H_2 in the U.S. (and most other countries) is currently natural gas. The nearly adiabatic partial-oxidation/reformation/shift reactions use at least 3 kg of natural gas (90% CH_4) to produce 1 kg of H_2 plus 9.5 kg of CO_2 [*7*]. When natural gas becomes too expensive, coal is chosen, which results in the release of over 16 kg of CO_2 per kg of H_2. Then, over 3 kg of coal must be burned (releasing another 10 kg of CO_2) to generate the 10 kWhr (36 MJ) needed to purify and liquefy 1 kg of H_2 [*14*], as required for efficient distribution. *The energy efficiency in producing LH2 from natural gas ranges from 40-50%, depending on plant size.* (This range has not budged in 15 years. We're too near Carnot limits.) The energy content of 1 kg of H_2 is equivalent to about 3 kg (~1.06 gal.) of diesel, which contains only 2.5 kg of carbon, generating 9 kg of CO_2.

At 70 miles per gallon and assuming 85% efficiency in the production of fossil diesel, the advanced fossil-diesel hybrid achieves about 7 miles per kilogram of total CO_2, while the bio-diesel vehicle could achieve infinite miles/kg of fossil CO_2. The next-generation Honda FCX may get up to 57 mi/kg of H_2. At this rate, it achieves 1.9 to 3 miles/kg of total fossil CO_2, depending on the H_2 production and distribution methods. Hence, when miles/kg of total fossil CO_2 ("fossil mileage") is fairly calculated, the total CO_2 generated per mile by a hydrogen vehicle is likely to be 2.5 times that of a comparable fossil-diesel-powered hybrid vehicle. The proposed hydrogen economy will do nothing to reduce CO_2 emissions. Rather, it will greatly increase CO_2 emissions – not just for a few decades, but until renewable hydrogen becomes competitive or scores of new, advanced, nuclear power plants are built. Fortunately, this option does not look as grim as it did a few years ago, owing to recent progress in the Radkowsky fuel cycle [*37*].

The Radkowsky Nuclear Fuel System. The IAEA concludes the total global uranium reserves (5-6 million tones) of good quality are sufficient to sustain current nuclear power plants, with a 2% annual growth rate, only through 2045. Others have recently concluded that even with near zero growth the high-grade ores (those greater than 0.15% U) will be depleted within 25 years [*36*]. Moreover, fifteen years after the high-grade ores are depleted, we could be into the very-low-grade ores (below 0.02% U), which may have negative energy balance and result in more CO_2 emissions (during the ore refining, processing, disposal, etc.) than would be produced by gas-fired power plants. Historically, the price of uranium has been artificially low as a direct result of state funds invested in the nuclear industry, which world-wide over the past 50 years have exceeded $300B in current dollars. However, the price of natural uranium has increased by a factor of five over the past five years, as annual consumption now exceeds mining production by over 50% [*40*]. It seems likely the price of uranium will increase by another factor of four (to $150/lb) by 2012 (at which point conventional nuclear power will not be competitive with wind), and it will likely exceed $500/lb by 2040. Nuclear options must have at least a 60-year time horizon, but they must also be practical today.

The up-side to soaring uranium prices is that more attention will be directed to advanced nuclear designs that will quickly permit an order of magnitude more energy from nuclear resources – and ultimately two orders of magnitude more. The most promising near-term option appears to be the Radkowsky thorium/uranium fuel system [*37*]. Its advantages include: (1) much more energy available; (2) much more proliferation resistant; (3) easily configured to burn up existing plutonium of all grades; (4) much less waste to store; (5) less toxic waste; and (6) more compatible with high burn-up of long-lived waste isotopes.

This is not your grandfather's thorium/uranium cycle. It is significantly different from other designs because it utilizes a structured fuel package that separates the fissile seed from the fertile material. In its first implementations, it will be a once-through design with no reprocessing, so it is not a "breeder" in the normal sense. Even so, it increases the available fission resource by an order of magnitude, partly because thorium is four times more abundant than uranium.

Radkowsky's idea was to construct special fuel assemblies that could be used in typical water-cooled reactors with very little modification. These units are made up of a central seed region containing fuel rods filled with reactor-grade uranium (that is, having no more than 20 percent uranium-235) and waste plutonium. Surrounding the seed is a blanket region with fuel rods containing thorium and natural uranium. Having uranium-238 in the blanket prevents anyone from withdrawing these rods and using only simple, chemical means to separate out the fissionable uranium-233 that is created over time. In fact, it would be much more difficult to make a weapon from this waste than from raw, natural uranium ore.

The fertile blankets will have a residence time of about 10 years. There will be a reduction in the volume of radioactive waste of a factor of two and a reduction in plutonium of a factor of 5. Moreover, the plutonium generated can more easily be reprocessed for subsequent burn up. Even without reprocessing, it should permit nearly a factor of 10 increase in total nuclear energy available from economic resources compared to what would be available with conventional reactors. Ultimately, more advanced reprocessing would be brought on line which would increase the amount of energy available by well over another order of magnitude – enough to power our world for a millennium. Research and development is currently being supported at a very modest level by DOE at MIT and elsewhere.

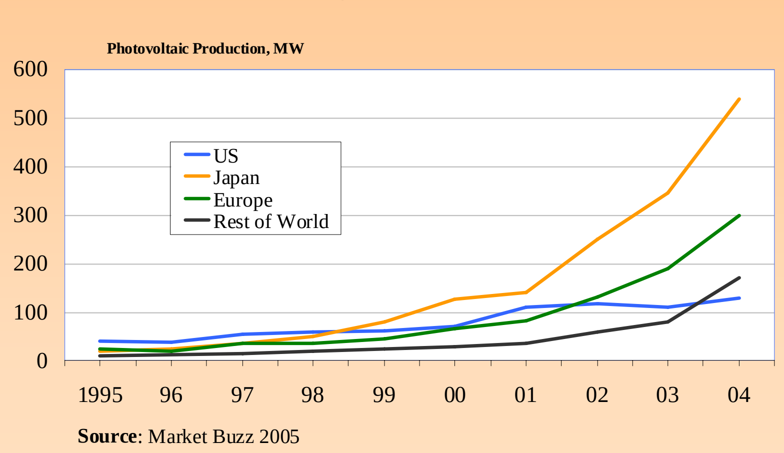
Quite a bit of investment and time will be needed to get the Radkowsky fuel processing infrastructure in place, but then the cost should be similar to current nuclear power costs. Hence, there may not be a long-term energy problem, but this solution makes it even more imperative that we quit wasting uranium in current once-through power plants, as enriched uranium is an essential component of the fuel in advanced uranium/thorium high-burn-up plant designs – at least after we burn up the more than 200 tons of excess weapons-grade plutonium and the many hundreds of tons of lower-grade plutonium scattered around the world today. Why hasn't the Radkowsky design been implemented yet – industrial inertia, cheap uranium, and a lack of political leadership.

Clearly, the biggest impediment to moving forward in this country with advanced nuclear options is the political difficulty of dealing with the waste issue. While the once-through Radkowsky cycle reduces the amount of nuclear waste, it will remain a huge issue until we accept advanced reprocessing. The enormous advances in robotics over the past decade will make it much easier to implement more effective reprocessing than was previously possible, and there really is no other responsible option. The 54,000 tons of high-level waste currently piling up at 104 nuclear plants around the country will exceed the 70,000 ton capacity of the proposed Yucca Mountain facility within two decades. An advanced reprocessing facility could begin extracting useful fuel from this waste and greatly reducing the amount of waste left for storage in a long-term repository. Perhaps the easiest way to begin the waste reduction process would be to begin incorporating high-level waste products into the fertile blankets of advanced Radkowsky plants.

Still, if recent history is to be a guide, it seems highly unlikely that advanced nuclear options will begin to make a significant contribution to our energy needs in less than 15 years, and it will take another 10 years under an optimistic scenario to see sufficient power production from them to begin to push electricity prices down. Perhaps by 2030 it will become economically practical to begin producing hydrogen using nuclear energy rather than coal and natural gas, but this expensive hydrogen will be needed for fertilizer and industrial applications as fossil sources become depleted.

Renewable Hydrogen. Wind energy is now a viable power option in many localities. If used for hydrogen production without a hydrogen gas line to the wind farm, the hydrogen would need to be liquefied for transport. To generate and liquefy 10 tons/day (one rail-tanker per day on average) would require at least 100 MW installed rated capacity for 30 MW average capacity, which requires 200 wind turbines of 39 m span in a Class 5 site [*38*]. This assumes 80% electrolysis efficiency, even though 65% is currently more common, as there is good reason to expect 80-85% will eventually be practical in large facilities when energy is more valuable. Liquefaction efficiency is assumed to be 60%, though lower efficiencies are currently achieved in plants of this size. The capital cost of the wind turbines (installed) would be about $60M-90M, and the effective power cost (20 year payback) is expected to be about $0.04/kWhr within a decade [*39*]. This could make the wholesale cost of LH2 at a very large wind farm (at a choice location) as low as $5/kg within 10 years, assuming substantial progress in cost reduction of electrolysis equipment (which seems probable, [*7, 40*]) and continued progress in wind turbine technology. The cost of carbon-fiber-reinforced composites has dropped by more than an order of magnitude in the past decade, and that trend should continue for several more years, at which point they will begin to make significant penetration into wind turbine manufacturing. Hence, there is good reason to expect continued progress in turbine cost reduction over the coming decade, especially for non-synchronous power applications, as for hydrogen or ammonia production.

The amount of wind energy available worldwide in Class 3 sites (6.9 m/s), and higher, is at least seven times the current total world energy usage [*41*] (more recent estimates are even higher), and many of these sites are expected to be economically practical. Thousands of excellent locations can be found for wind farms in the Dakotas, Kansas, Wyoming, Great Lakes region, and elsewhere, and the trend of decreasing costs of wind turbines will probably continue for at least another decade. However, until such time as we are no longer using coal to power the grid within at least 1000 km of wind farms, it seems that the best use of this wind energy would be to put it into the grid, as this would not require wasting 50% right off the top for electrolysis and liquefaction [*30*]. When surplus wind energy becomes available is select regions, perhaps the best use of it would be to produce ammonia for renewable fertilizers, as ammonia is much more easily trucked than hydrogen and ammonia production currently accounts for about two-thirds of our total hydrogen usage. The cost of fertilizer in the U.S. doubled between late-2002 and late-2005. With natural gas prices likely to be above $12/GJ within a year, electrolysis hydrogen from wind in Class 5 sites should soon compete favorably with natural gas for chemical fertilizer production, hydrocracking of heavy oils, and hydroforming of fuels. Nearly 400 GW of installed wind power (30 times the current world-wide installed base, and 4 times the current stated U.S. goal for 2020) would be required to produce all the hydrogen needed for these industries in the U.S. Such a massive scale-up in wind energy could eliminate U.S. dependence on imported LNG for many decades and dramatically reduce U.S. green house gas emissions.



Source: Market Buzz 2005

Figure 8. Increase in PV production, 1995-2004.

As shown in **Figure 8** photovoltaic (PV) production has risen sharply since 2001, thanks primarily to the investment in Japan and Germany. The cost of PV cells has dropped by a factor of three in the past decade and is now about $6/W, which works out to about $0.18/kWhr for energy in many locations [*42*]. Though Japan's strong support for solar may soon end, GE and California are ready to take over, and another factor of two drop in cost is expected in the next decade [*42, 43*]. This could potentially bring the cost of PV-generated bulk hydrogen gas at a large plant down to $8/kg; but, as seen from Fig. 3, that is still twice the projected cost of bulk hydrogen gas from fossil sources twenty years from now. It is also important to keep in mind that the cost would likely be twice this for the private home owner, because of the relatively high costs and poor efficiency of small electrolyzers, purification equipment, compressors, and storage tanks. There would also appear to be unacceptable hazards associated therewith.

Hydrogen from biomass (pyrolysis and water shift) using waste biomass (from logging, paper mills, farming, and clearing) is about 10% more expensive than hydrogen from coal without sequestration [*7*], but this is not likely to be a significant source, as waste biomass is limited and is likely to be more valuable in the production of bio-methanol and biodiesel, as will be discussed shortly. Orbiting or lunar solar microwave stations beaming power back to earth appear to have little more practical basis than cold fusion, and even the optimists don't expect Tokamak fusion reactors to be providing power to the grid in less than 40 years.

As noted earlier, breeder reactors appear quite improbable for at least two decades, but they do seem to offer the real possibility of a nearly limitless energy supply. There are clearly huge safety and proliferation issues associated with the notion of breeder reactors, as advances in robotics will only make it easier for terrorist groups to build powerful nuclear weapons from the plutonium-rich waste and intermediate products from breeder reactors and fuel reprocessing plants. And there are huge technical issues, as attested to by 40 years of failed attempts to demonstrate an operating cycle [*36*]. Still breeders seem about two orders of magnitude more practical than fusion reactors, and the efficiency with which a breeder reactor should in principle be able to utilize natural uranium suggests they may make it cost effective to extract uranium from the sea (even at $1000/kg, 12 times the current price, and about three times the extraction price estimated by one study), where there is probably enough to power breeder reactors supplying energy for the entire world for millions of years. Although the above suggests breeder reactors are eventually inevitable, it does not imply a hydrogen economy is, as it will still be more cost effective to distribute their energy via electricity, and it will still be much more practical to utilize liquid biofuels for transportation, even if electrical energy from breeder reactors sixty years from now is half the cost of raw bio-energy.

Hydrogen Hype. How could such a well-intentioned scientific endeavor as clean energy stray so far from reality? Perhaps like this. For three decades, it has been pretty clear to many concerned scientists that our world's cheap oil supplies would be largely depleted within their lifetime and major changes would be forced upon us. Moreover, it was common knowledge in the mid-1970's that hydrogen fuel cells for more than a decade had achieved up to three times the efficiency of gasoline engines, and very cheap natural gas resources (hence, hydrogen) seemed inexhaustible. It was reasonable to expect that major progress could be made in reducing the manufacturing cost of fuel cells, so the notion of a hydrogen economy, ultimately based on nuclear power plants, seemed to have economic merit. Undoubtedly, the fact that the basic reaction was conceptually based on fifth-grade chemistry also contributed to its popularity.

It would then take more than two decades (until early 2001) for five major realities to begin to be appreciated by a few scientists. First of all, order-of-magnitude cost reductions in manufacturing processes are almost never realized after the fourth decade of development. Secondly, the efficiency of ICEs would steadily improve. Thirdly, global warming would have to be seriously addressed much sooner than most had expected. Fourthly, the price of natural gas in many areas would skyrocket early in the 21st century as demand began to exceed local supply. And finally, nuclear power would not be accepted again for many decades.

As long as the sales revenue in any developing industry is an order of magnitude smaller than other sources of revenue (such as investment capital and federal grants), the product sales prices are likely to be severely underestimating actual production costs. However, if we can believe the reports that rather massive, low-efficiency (31%), 75 kW PEMFCs for non-mobile use, now perhaps in small scale production, can finally be produced for about $2500/kW [*7*], then it seems reasonable to project that the production cost for vehicle-grade PEMFC systems might be ~$5000/kW at a similar (small) production scale. Current commercial experience in the DMFC industry points to the same price as being realistic for small-scale production. Ford is currently estimating the production cost of their 1600 kg Focus FCV (with an 85 kW FC stack) will be about $350,000 each in quantities of 30 units per year [*44*]. Of course, a cost reduction of two orders of magnitude is possible when going from first experimental prototypes to large scale production, but that opportunity is long past. As previously noted, over a billion dollars has already been expended on the central issues of manufacturability and reliability of fuel cells over the past two decades, and they have been in small scale commercial production for five years. The available opportunity is going from small scale production to large scale production. Manufacturing history suggests a factor-of-six reduction in cost is about the limit that can be expected here. The catch is that high-volume production will never materialize (even if a fully adequate fueling infrastructure were completed by 2020), given the (A) short time (perhaps 8 years) that natural gas would still be available at a semi-tolerable price, (B) serious global warming issue with hydrogen from coal, (C) serious safety issues with hydrogen fuel, (D) short FC life in vehicles, (E) limited driving range of hydrogen vehicles, (F) poor tolerance of PEMFCs to normal environmental conditions, and (G) competition from next-generation liquid biofuels in advanced ICEs.

There are several possible explanations for the continuation of the hydrogen hype. It is possible that some have seen a security reason for deliberately hyping hydrogen even after the above facts began to be appreciated. For example, one can certainly argue that it is in the U.S. security interest for Russia's oil reserves to become depleted to below U.S. reserves while oil prices are low. The best way to achieve this is to convince the oil exporting countries they must pump out all of their resources before the hydrogen economy makes their oil resource obsolete. Keeping the price of oil low hurts the oil exporting countries, the second largest of which is Russia. As bizarre as this suggestion sounds, it is actually supported by statements from high-level Middle-East oil ministers [*22*]. But probably the main reason that hydrogen hype shows little evidence yet of abating is inertia – in research, business, and politics. The careers of thousands of scientists, businessmen, and politicians are now bound up in the hydrogen hoopla. (It has also been observed that a number of current U.S. administration high-level officials and family members have notable holdings in companies involved in the platinum-group metals needed for PEMFCs.) It seems unlikely that evidence of pervasive scientific flaws will be sufficient to change many minds very quickly on this subject. Our best hope for progress comes from the rapidly rising prices of oil and gas over the past four years, which are likely to result in greatly increased funding of developments that can make a difference within the next decade.

Clearly, we must take seriously the fact that the world will soon be running out of cheap, fossil oil; and if we don't prepare by developing viable alternatives, the economic consequences will be severe. Focusing all our efforts on a single dream that seems less and less likely to be of any practical benefit is worse than doing nothing at all because of the false hope it engenders. Simply put, hydrogen will never compete with liquid biofuels in the transportation arena.

Sustainability via Next-generation Liquid Biofuels. It's surprising how few people (even among those who study these issues) understand that bio-fuels needn't contribute *at all* to global warming. When biomass is burned, the carbon is just going back to where it was a few months or years earlier – before the plants took it out of the atmosphere [*45*]. In fact, intensive cultivation of biomass often results in additional carbon being sequestered in the soil, and thus really reduces atmospheric CO_2. It's true that current methods of producing fertilizers release quite a bit of fossil CO_2 and farming has used petroleum diesel, but it needn't be that way [*26*]. Anaerobic digestion of animal waste is an economically viable source of fertilizers and could soon begin making a significant contribution to our methane needs [*46*]. And as mentioned earlier, wind can be used to make renewable fertilizers.

The fossil energy balance (ratio of chemical energy of the biofuel plus co-products to the fossil energy required for fertilizing, growing, harvesting, and processing minus processing energy derived from the raw biomass) for ethanol from corn has increased steadily over the past decade from 1.2 in the early 1990s up to 1.57 to 1.77 today, depending mostly on the processing method [*47*]. However, there are a large number of promising options for biofuels with much higher efficiency and much lower environmental impact. Ethanol from sugar cane, with fossil energy balance well above 5, is clearly the most cost effective and efficient biofuel today in climates where sugar cane thrives. Over 5 billion gallons of ethanol are currently being produced annually in Brazil (about 25% of gasoline usage) at $0.8-1.1/gal (depending on the producer), and ethanol production there may exceed 80% of their private transportation fuel usage within a decade [*48, 49*]. They are expecting ethanol exports to double to $1.3B by 2010. India, the world's second largest producer of sugar, is also rapidly ramping up their ethanol production.

It is probably necessary to acknowledge here that a few scientists (with oil-money support), most notably David Pimentel and Tad Patzek, have calculated energy balances in the range of 0.45 to 0.7 for all biofuels, and they continue to occasionally get an article published in peer reviewed journals [*50*]. Their analyses (1) use fertilizer application rates that are too high (except for nitrogen) by 20-50%, (2) apply energy requirements that were valid in the mid-80s for urea (the most energy intensive fertilizer) to much of fertilizer production, thus overstating it by nearly a factor of two [*51*], (3) use ethanol distillation plant efficiencies from the mid-80's, (4) ignore the enormous value of co-products [*47*], and (5) include excessive amounts (by a factor of four) for process plant depreciation. They also include excessive energy and costs (by at least 30%) for herbicides, seeds, and environmental degradation. (See [*47*] for a more detailed analysis. Regarding NH_3 production, for example, the mean for plants built in the 1960s was 75 GJ/t, while for some new plants now it is under 30 GJ/t.) Of course, it is also important to acknowledge that the calculations by the biofuel supporters usually assume best practice, and the reality can be quite suboptimal. Nonetheless, the progress in efficiency gains over the past 25 years, especially in fertilizer production and fuel conversion processes, during a period when fossil energy has generally been very cheap, has been remarkable. The rapidly rising costs of fossil energy over the past four years will undoubtedly lead to much higher efficiencies in all agricultural and biofuel processes over the coming decade.

The progress in ethanol production efficiency in Brazil is illustrated graphically in **Figure 9**, where the price paid by the government to ethanol producers has continued to fall even over the past four years while the price of oil has rapidly increased [*49*].

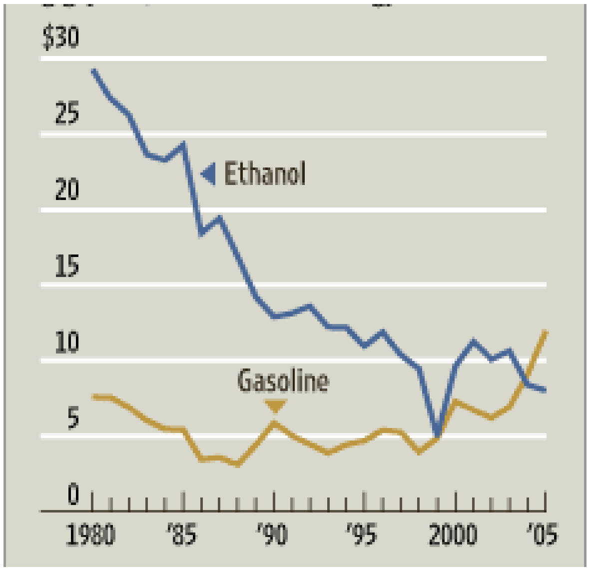


Figure 9. Price per GJ of ethanol in Brazil and the international price of gasoline.

Cellulosic bio-ethanol (especially from switchgrass, but also eucalyptus, hemp, poplars, pines, and all types of wood wastes) is steadily becoming more competitive [*26, 52*]. It promises net efficiency well over 40%, fossil energy balance exceeding 5, with no depletion (in fact, augmentation) of soil organic material.

(Net efficiency is the energy of the biofuel divided by the sum of the total chemical energy of the raw biomass plus all production energy inputs.) The primary problem with cellulosic ethanol has been the cost of the enzyme, cellulase, needed to convert the cellulose into glucose for fermentation into ethanol. Fortunately, there has recently been major progress here that has reduced its cost by an order of magnitude [*53*], and further dramatic cost reductions are anticipated in the next few years [*54*]. This will allow ethanol to be produced from waste wood and paper at prices significantly below the current pre-tax cost of gasoline per unit energy. However, advanced diesel engines will still be 50% more efficient than even next-generation spark-ignition ethanol engines, so bio-diesel may be even better.

Bio-diesel from waste animal oils (including tallow and lard) and current oil crops is also a significant resource [*55*]. Rape seed is currently the best oil crop, and other excellent oil crops that do well in many places include peanuts, olives, sunflowers, mustard seed, sesame, and pumpkin seed [*56*]. Biodiesel production in the U.S. in 2004 was under 25 million gallons, but it is expected to grow to 120 million gallons annually within a few years, largely because of the new fuel tax credit and the rapidly increasing price of fossil diesel. It has been thought that biodiesel could only deliver about one billion (B) gallons per year (less than 1% of U.S. needs) before the market for the glycerin byproduct is saturated, at which point biodiesel becomes 25% more expensive. But hydrocracking of glycerin into simple alcohols, which is just beginning to be studied, seems likely to address this concern. Other possibilities are bio-methanol, higher alcohols, straight vegetable oils, and high-oil algae, none of which are currently being pursued in a major way.

The transesterification process required to produce the methyl ester (biodiesel) from vegetable oils contributes some to its cost. It is possible to use many straight vegetable oils in slightly modified diesel engines. Hobbyists have achieved very promising preliminary results by simply including a fuel warmer to facilitate starting. However, it is not yet known whether this option can compete with the advanced diesel engine in either efficiency or engine maintenance costs.

Methanol is a major commodity chemical (over 10 million tonnes/yr) that is efficiently produced from high-pressure-catalyzed syngas ($CO + H_2$), usually from natural gas, but syngas can just as easily be produced from gasification (pyrolysis) of any biomass. Biomethanol, from biomass (especially wastes and woody biomass), may be a more economical source for biofuels. Woody biomass can be converted to methanol with up to 61% efficiency [*57*], and the additional energy required for harvesting and fertilizing may be quite low for switchgrass, hemp, poplars, and eucalyptus. Moreover, when the waste heat from the methanol plant can also be utilized for space heating or Combined Heat and Power (CHP), the total biomass energy utilization rises to 67-82% efficiency [*57*]. The primary challenge still is the competition from natural gas, as recently developed liquid-phase oxidation methods promise to produce methanol from methane at costs under $60/ton, plus the cost of the methane, which will continue to be quite cheap in some remote locations for several decades.

The woody biomass wasted each year (primarily from logging operations, construction site clearing, and saw mills) in the U.S. is estimated to be sufficient to produce over 12B gal of biomethanol, from which perhaps 5B gal of biodiesel could be produced, as discussed shortly. The dark liquor waste from domestic paper mills could produce several times that amount of biomethanol [*58*]. Switchgrass can produce 11 tons of dry, woody biomass per acre (about 0.4 hectare) per year [*59*], which should be sufficient for up to 2000 gallons of biomethanol, or perhaps 800 gallons of biodiesel, or ultimately up to 1100 gallons (currently, 750 gallons) of cellulosic ethanol. Hemp may have even higher biomass yields in many climates [*60*].

Efficient, moderate-sized methanol plants have been built to produce 83,000 tonnes (28 million gallons) of bio-methanol per year, which require about 12,000 to 40,000 acres for sustainable harvesting, depending on the climate [*52, 57*]. Currently, the cost of a plant of this size is roughly $100M, and the cost of a biomethanol plant of five times this capacity is roughly three times as much, while cellulosic ethanol plants may be somewhat more expensive.

A small but still significant part of the operating cost with biomass can be the transportation of the feedstock to the processing plant, even for dedicated biomass land use. For dual-use lands, the transportation costs can go way up, so smaller bio-mass plants could be more cost effective, though plants below 3 million gallons per year have not been cost effective. Hence, we may see a future with thousands of bio-mass plants scattered throughout rural and suburban areas. (Obviously, there are huge economic and social implications involved here – especially, enormous rural job creation and the long-awaited recovery in the chemical industry.) Some of the product would be used locally, but most of the bio-methanol would be trucked or piped to refineries to be converted to diesel, gasoline, and jet fuel.

One might consider using straight biomethanol as a vehicle fuel, though its effective fume toxicity is greater than that of gasoline when its higher vapor pressure is also considered. It also has low energy density (50% that of diesel, by volume), and it is not yet clear that either DMFCs or methanol-fueled ICEs can exceed 35% efficiency in practice. Diesel is a better engine fuel, and methanol can efficiently be converted to diesel (or gasoline) via dehydration to ethylene followed by reformation chemistry similar to, but more selective and efficient than, conventional Fischer Tropsch synthesis, generally referred to as Fischer Tropsch Type (FTT) chemistry [*61*]. However, 20% methanol in gasoline has very recently been shown to be more effective than either MTBE (methyl tertiary butyl ether), tetraethyl lead, or ethanol additions in improving efficiency and power and in reducing emissions [*62*].

Novel Biofuels. One of the advantages of the gasification/Gas-to-Liquids (GTL) processes is that the input can be any type of carbonaceous material, including farm waste, sewage sludge, and cheap coal. While operating and maintenance costs are likely to be higher for gasification of very dirty feed stocks into clean syngas, the feed stock itself may have negative cost – i.e., the waste producer may be willing to pay to dispose of it. It's also worth pointing out that relatively minor changes in the methanol GTL process allow it to become an efficient ammonia process for renewable fertilizer. Of course, the gasification process can also be modified to produce high-purity hydrogen with high efficiency, though that does nothing to address the enormous storage, distribution, safety, and engine cost issues still associated with hydrogen. Other bio-hydrogen processes [*63, 64*] are currently more costly and problematic.

Modifications of GTL processes allow efficient production of a mixture of higher alcohols, including ethanol, propanol, butanols, pentanols, and hexanols, from syngas [*65*]. High-alcohols have several attractive characteristics as fuels. They have extremely low fire hazard, very high octane rating, relatively low toxicity, low vapor pressure, high energy density (85% that of diesel, by volume), and are water soluble and bio-degradable (which allows them to be shipped without environmental concern in old, surplus, single-hulled tankers). The mixed-alcohol process is being developed primarily for improved gasoline oxygenates and octane enhancers [*66*], but there is reason to believe that ICEs burning straight mixed-alcohol fuels could achieve ultra low emissions and efficiencies close to those of diesel engines. The methanol-from-methane plant shown in **Figure 10** (Denver area), may soon be converted to this process.

While these high-alcohol GTL processes are still not publicly well characterized, it seems likely they could become very cost-effective. For example, it seems reasonable to assume that the kind of progress seen recently in cost reduction of methanol from methane (including liquid-phase processes) can be extended to higher alcohols. In fact, a significant concern is that it may be possible to produce mixed-alcohol fuels, with no on-site CO_2 emissions, from a mixed feedstock of stranded gas and coal so cheaply that biomass sources, which are essential for global warming mitigation, may have difficulty competing for three more decades. (Of course, the demand for the stranded gas for other growing markets may keep it relatively expensive, so biofuels may still compete.) All GTL processes that do not utilize at least 75% methane as the feedstock also release considerable CO_2, which is a concern if the feedstock is not predominately biomass. If cheap renewable electricity is available locally (e.g., from a nearby wind farm), electrolysis hydrogen can be used to efficiently convert the waste CO_2 from the GTL plant to additional biofuels [*66*], especially alcohols.

Figure 10. A small (1000 bbl/day) reactor for methanol production being considered for modification to production of higher mixed alcohols.

Another promising option under investigation is breaking down clean biomass and separating it into digestible carbohydrates, protein, and remaining biomass (lignins, etc.), with the protein being used as animal feed, the carbohydrates being turned into ethanol using biological or catalytic processes, and the remaining biomass being converted into bio-diesel or alcohols via a thermo-chemical process.

A particularly promising recent development involves the acid-catalyzed conversion of carbohydrates in aqueous solution with pressurized hydrogen to liquid alkanes ranging from C_7 to C_{15}, from which gasoline and diesel are then efficiently produced [*68*]. This process promises to achieve much higher efficiency than established ethanol processes, as it eliminates the most energy-intensive step – distillation.

Although the chemical-process-equipment industry is mature, production of the specialized plants needed for bio-methanol, cellulosic ethanol, aqueous-phase processing of carbohydrates, higher alcohols, and biomass separation is still in its infancy. Hence, there is good reason to believe substantial cost reductions will be possible in the future.

Another promising source for biodiesel is high-oil algae. Estimates suggest 100 billion gallons of biodiesel could be produced from 10,700 square miles of salt-water ponds in relatively small farms in the desert. Perhaps enough biodiesel to replace all petroleum transportation fuels in the U.S. could be grown in roughly 10% of the area of the Sonora desert in the Southwest [*69*]. It has been estimated that it would cost about $200B to establish these farms and $50B/yr to operate them to the point of yielding algae feedstock for the refineries. Perhaps it would cost another $40B/yr to produce the biodiesel from the algae feedstock, but all of these estimates have high uncertainties – especially the cost of delivering the hundreds of millions of tons of CO_2 (from coal power plants) and other nutrients to the ponds. Distributed approaches, especially growing the algae off municipal waste streams, may be even more attractive.

Conclusion. Will bio-mass be adequate for the longer range outlook, sixty years from now? Undoubtedly, wind, solar, and clean coal with carbon sequestration will play a larger role, and we'll see lots of plug-in hybrid vehicles with advanced batteries. Perhaps we'll also see biofuel plants located near huge wind farms in favorable areas for enhanced production of higher mixed bio-alcohols. But the primary intermediary in transportation will still not be hydrogen – not even in countries where there is no spare farm land capacity for biofuels. Hydrogen simply isn't the best way to distribute energy [*70*] or to power vehicles, nor is it the best way to address the global warming challenge. We'll still be pumping liquid fuel into our tanks – whether it will primarily be biodiesel, ethanol, or high-alcohols is yet to be determined. And the huge international petroleum trade may largely be replaced with international trade in biofuels. For now, our first priority should be useful (practical) solutions for the next five to thirty years that simultaneously address climate change, energy needs, and economic growth.

In 2003, the U.S. DOE commissioned a study by the National Academies of Engineering to review the hydrogen initiative [*7*]. This report bluntly points out the serious challenges facing fuel cells and notes that it is unlikely they will have a significant effect on oil imports or CO_2 emissions during the next 25 years. However, this report still only takes cautious steps and fails to appreciate the urgency of the need for viable energy alternatives – possibly because it was completed before major reserves overstatements by several large energy firms had surfaced, before the DOE/EIA had begun to admit that serious oil and gas shortages may develop within several years, and when oil was under $35/bbl.

The evidence for both an impending energy disaster and a climate disaster if we do not respond in meaningful ways is becoming irrefutable, and the scientific case against hydrogen as a transportation fuel is also now undeniable. Five years from now, in hindsight, the hydrogen program will look more like a ruse then naive scientific exuberance if major changes in energy programs are not forthcoming in response to these scientific challenges. Simply changing priorities in existing hydrogen R&D programs will not bring a useful solution within 30 years and probably not within 70 years, as futuristic energy technology projections beyond five years by scientific organizations have a history of being overly optimistic. (For example, controlled fusion has been 40 years away for the past 50 years.) We must rapidly ramp up all available promising renewable options to lessen the effects of $150/bbl oil, $25/GJ natural gas, $200/kg uranium, and major climate catastrophes, probably within a decade. Major investments are needed into bio-methanol, cellulosic ethanol, advanced biodiesel crops, mixed-alcohols, high-oil algae, and advanced catalysts for biofuels from bio-syngas. It's time we start putting some serious money into real options for renewable energy to address global warming and our future transportation needs.

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