Our Transportation Energy Future

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There can be no doubt the *status quo* cannot continue for more than a few decades in automotive transportation, but we cannot forget the economic and social lessons of the past forty years from other power dreams, such as conventional fission, fusion, and orbiting microwave power stations. It is becoming increasingly more clear with each passing year that hydrogen fuel cells will not be practical, and our only viable, long-term option is renewables.

Nobel Laureate George Olah (Chemistry) and many others have commented that a "Methanol Economy" seems much more practical than a "Hydrogen Economy" [*1*]. 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 (gasoline, diesel, jet fuel, etc.) and products currently obtained from fossil sources. Many other biofuel pathways may prove even more practical. The energy balance of corn ethanol, one of the least viable biofuels, has increased from about 1.05 to about 1.8 over the past 15 years, and similar progress seems likely over the coming 15 years. Cellulosic bio-ethanol (especially from switchgrass, but also eucalyptus, hemp, poplars, pines, and all types of wood wastes) is steadily becoming more competitive. It promises fossil energy balance exceeding 5, with no depletion (in fact, augmentation) of soil organic material. **Figure 1** shows that sugar-cane ethanol (which is no longer subsidized) in Brazil is now less expensive, per unit energy, than gasoline.

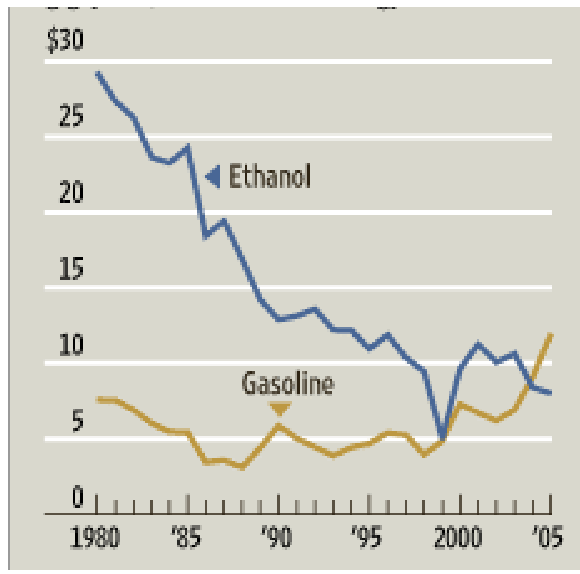

Figure 1. Price per GJ of ethanol in Brazil and the international price of gasoline.

While there may be some economically viable applications for hydrogen fuel cells, fuel cell vehicles (FCVs) face daunting challenges in all areas – fuel cost, engine cost, reliability, fuel safety, and CO_2 emissions. However, the real death knell to the hydrogen dream is, in a nutshell, the competition from advanced biofuels in advanced internal combustion engines. With wind-generated chemical fertilizers and biodiesel-powered farm implements, the fossil CO_2 released from the economical, convenient, biofuel-powered hybrid vehicle will approach zero. In the following sections, we briefly review each of the major hydrogen challenges and then summarize some promising biofuel options.

1. Realistic hydrogen cost projections. Current U.S. H_2 production is enormous – about $2x10^{10}$ kg/yr. Yet, the current pre-tax cost of liquid hydrogen (LH2) in the U.S., delivered in 15,000 gallon (4300 kg) tankers to high-volume customers is about \$7/kg. The cost of pressurized H_2 for consumers has been in the vicinity of \$100/kg (current dollars) for over thirty years. Some studies have concluded mass produced mini-reformers at corner filling stations could provide hydrogen from natural gas at \$3.4-4.3/kg [*2*], but other studies suggest the price would be at least five times higher at likely commercial prices for natural gas fifteen years from now [*3*]. Current proven domestic natural gas reserves will last only ten years, and there is increasing pessimism about future domestic discoveries [*4*]. The price of natural gas in the U.S. has increased by a factor of ten in the past thirty years and a factor of three in the last six years. Until quite recently, most analysts have predicted sufficient natural gas reserves worldwide for the next 30 to 50 years. However, a recent, detailed global gas resource analysis, published in the Oil and Gas Journal, now predicts global conventional gas production peaking in 2019 [*4*].

On the other hand, the current U.S. pre-tax cost of diesel for the individual consumer at the local station is about $0.7/kg. Of course, we need 3 kg to equal the energy of one kg of H_2, but that still leaves an order of magnitude cost advantage for diesel per unit energy. Realistic estimates suggest the pre-tax price of various biofuels should soon be competitive (per unit energy) with fossil fuels and will stay competitive.

2. Fuel-cell engine costs. The only possible type of hydrogen fuel cell for automotive applications is the proton exchange membrane fuel cell (PEMFC), also called PEFC (polymer electrolyte fuel cell), as all other types are either far too massive or have unacceptably short lifetimes. The cost of PEFC engines (fuel cells, power conditioning, electric motors, etc.) is often reported to be in the range of 3,000-8,000 U.S. dollars per kilowatt – 100 times that of the common diesel engine, or fifty times that of the advanced diesel, which will soon exceed 58% LHV efficiency [*5*]. Inspection of the sales and financial data from one of the largest current producers of PEM fuel cells for non-mobile use (Plug Power) suggests current costs of PEM fuel cells (not including real R&D) are actually over $15,000/kW [*6*]. The cheapest, non-compact fuel-cells currently actually available on the market appear to cost $8000/kW [*7*]. It is worth noting that polymer FCs 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. Over the past twelve years, Ballard Power has furnished ~70% 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 recent fuel-cell engines has been over $1M each. Honda has estimated 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.

3. Fuel storage mass, volume, and safety. There has been enormous progress in cost reduction of carbon-fiber composites during the past decade. Still, an $8,000 carbon-fiber-wrapped (brittle) fuel tank achieving 11% H_2 storage seems too expensive for the small private car, and liquid hydrogen doesn't keep long. At 5000 psi, the volumetric energy density is only 10% that of diesel. The mechanical energy alone (ignoring the chemical energy) stored in the hydrogen tank may be five times that of a 50-calliber artillery shell, and the impact strength of light-weight tanks (especially, carbon-composites) is not high. 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.

4. Fossil CO_2 release. The only economically viable sources of H_2 in the U.S. (and most other countries) are natural gas and coal. 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 [*8*]. 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, which will be required for efficient distribution. *The energy efficiency in producing LH2 from natural gas is 40-50%*, depending on plant size. (This number has not budged in 15 years and will not in the next 50. We're too near Carnot limits.) The energy content of 1 kg of H_2 is equivalent to 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, the advanced fossil-diesel hybrid achieves 7 miles per kilogram of total CO_2, while the bio-diesel vehicle could achieve infinite miles/kg of fossil CO_2. The mileage of production-grade hydrogen fuel-cell automobiles is limited both by the low energy density of the fuel and the poor mean efficiency of PEMFCs. The next-generation Honda FCX, at 57 miles per kilogram of hydrogen, will achieve 1.9 to 3 miles/kg of total CO_2, depending of the H_2 production and distribution methods. Hence, when miles/kg of fossil CO_2 release ("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.

5. Infrastructure Development. Some have estimated that the development of an efficient hydrogen distribution infrastructure would cost only $300B, though other estimates are four times that amount. However, the fuel distribution infrastructure is very small compared to the required manufacturing infrastructure and vehicle replacement costs, which would likely exceed $7 trillion.

6. Hydrogen Hype. It is interesting to note that in 1998, the DOE expected 10,000 FCVs to be in use by 2005. More recently, they projected that will occur six years from now. If the DOE invests another $2B (as planned) over the next 5 years, a few hundred more demonstration vehicles (at perhaps $500K each) will probably be on the road, but that really doesn't get us any closer to a practical solution for private transportation for the future.

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 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 early gasoline engines, and our 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.

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, the price of natural gas in the U.S. would skyrocket early in the 21st century as demand began to exceed supply. Secondly, the efficiency of the advanced gasoline and diesel engines would steadily improve. (Diesel engines now exceed 50% and may soon exceed 58% efficiency. Gasoline engines have exceeded 30% for two decades and will soon exceed 38% efficiency [*5*].) Thirdly, global warming would have to be seriously addressed much sooner than most had expected. Fourthly, order-of-magnitude cost reductions in manufacturing processes are almost never realized after the third decade of development. And finally, nuclear power would not be accepted again for many decades.

7. Responding to the mega-challenges via advanced biofuels. The quadrupling of the price of oil in the last six years should help convince us that the world will soon be running out of cheap, fossil oil [*9*]. And if we don't prepare by developing viable alternatives, the economic consequences will be severe. However, focusing all our efforts on a single dream that seems less and less likely to be of any practical benefit may be worse than doing nothing at all because of the false hope it promulgates. We also cannot ignore global warming, and we must accept the fact that hydrogen will do nothing to reduce CO_2 emissions. Rather, it will increase CO_2 emissions – not just for a few decades, but until we're ready to build hundreds of new nuclear power plants, and that's not going to happen soon.

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 promising renewable options to avert another doubling in the price of oil and major climate change in the not-too-distant future. Advanced biodiesel processes from waste and energy crops (mustard, rape, peanuts, sunflowers, sesame, soy, pumpkin, and high-oil algae) [*10, 11*], combined with hydrocracking of the glycerin byproduct into simple alcohols, are extremely promising in the near term [*10*]. Major investments are also needed into cellulosic ethanol [*12*], bio-methanol [*13*], and mixed-alcohols from poplars, pines, hemp, and switchgrass [*10*]. It's time we start putting some serious money into real options for renewable energy to address global warming and our future transportation needs.

And what about the longer range outlook, seventy years from now, will bio-mass be adequate? Undoubtedly, wind, solar, and clean coal with carbon sequestration will need to play a larger role, as will advance fission options. A particularly promising option (likely to receive increased attention now that the price of uranium has increased by more than a factor of five in the past five years) is the Radkowsky thorium/uranium fuel system [*14*]. 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.

But even if hydrogen is being produced at low cost at advanced fission power plants thirty years from now, the primary intermediary in transportation will still not be hydrogen. Hydrogen simply isn't the best way to power vehicles. It will never compete with biofuels in the transportation arena from any perspective – cost, safety, convenience, reliability, or sustainability. For now, our first priority should be practical solutions for the next thirty years.

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