Responses to Joe Romm’s Seven Points on the Hydrogen Economy

by C. E. Thomas, President, H$_2$Gen Innovations

#1 FCV Cost

Joe states that PEM engines now cost $5,000/kW, or $400,000 for an 80-kW system. To be competitive with ICEs, conventional wisdom holds that cost needs to fall to at least $50/kW for the FC plus hydrogen storage plus the electric motor (meaning that the FC system has to cost no more than $20/kW.) Joe says that it took PV and wind 20 years for a 10X drop in price, therefore the 100X drop that he portrays for FCVs would take many decades. He concludes that a major breakthrough in fuel cell technology is required.

Christine Sloane of GM reports that they are within a factor of 10 now (if mass produced) in the range of a few hundred $/kW without any breakthrough. DTI showed in the mid-90’s in a major report for Ford/DOE that costs could be reduced to the $50/kW to $80/kW range in mass production.

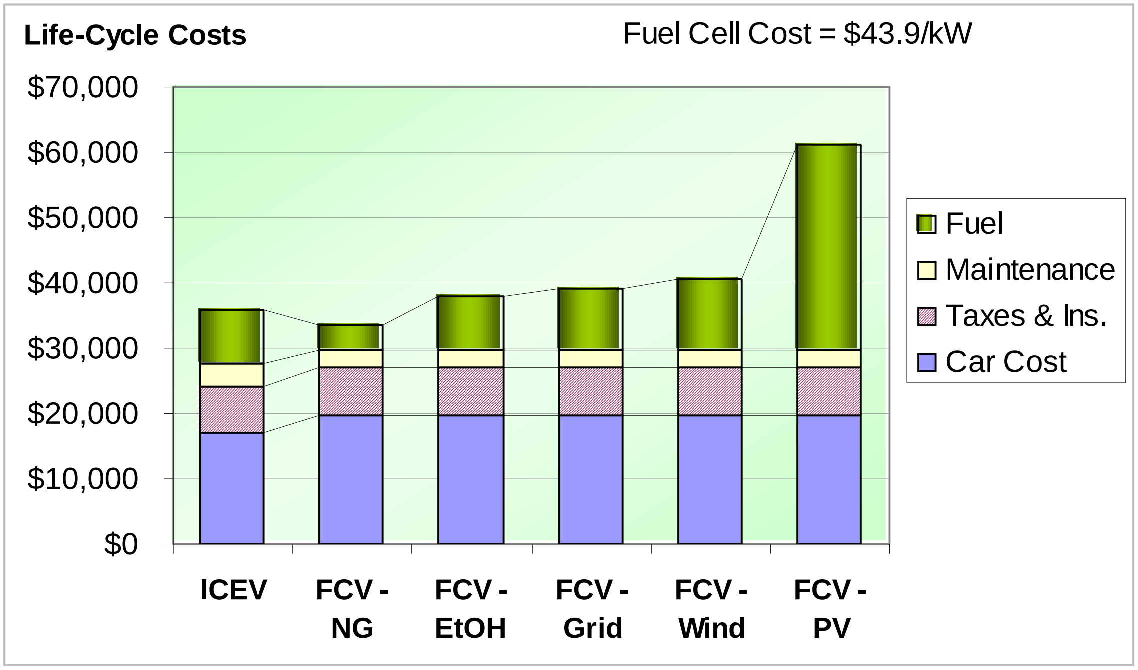
The Ford analysis showed the following costs for their FCV design based on the Mercury AIV (aluminum intensive vehicle) 5-passenger vehicle (“Initial FCV” below):

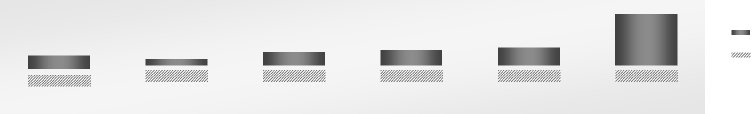
		Initial FCV	Advanced FCV	ICEV
Fuel Economy	mpgge	65.8	85.2	30
FC Power req'd	kw	38	29.8	
FC cost/kW	$/kW	43.9	52.1	
Battery Power req'd	kw	63.5	32.8	
Motor Power req'd	kw	101.4	65.6	
H2 Storage req'd	kg	4.61	3.56	
Capital Cost				
FC Cost	$	1670	1554	
Battery	$	1090	612	
Motor/controller	$	1058	776	
H2 Tank	$	1048	837	
Gear Box	$	200	200	
Other	$	150	150	
Total FC Drive Train	$	$ 5,216	$ 4,313	$ 2,425
Glider		15,575	15,575	15,575
FCV Price		$ 20,791	$ 19,888	$ 18,000
Delta w/r to ICE	$	$ 2,791	$ 1,888	-

H2Gen:Ethanol vehicles.XLS; Tab 'LCC';E 46 5/30 /2004

The “advanced FCV” was based on the PNGV (Partnership for a New Generation of Vehicles) advanced car body with lower aerodynamic drag (0.27 vs. 0.33), reduced cross-sectional area (2.08 vs. 2.13 m^2), lower rolling resistance (0.0072 vs. 0.0092), and lower weight (1,032 vs. 1,291 kg). These are both battery hybrid FCVs: a battery bank provides energy storage for acceleration, reducing the power required from the fuel cell system from 80 to 100 kW down to the 30 to 40 kW range. This very detailed analysis showed that, even if the fuel cell system cost $44 to $52/kW (excluding motor, controller, hydrogen storage and gear box), the total FCV cost would be only $1,900 to $2,800 more than a conventional gasoline car of the same size. Presumably some (many?) car buyers would pay this premium for a zero-emission vehicle that would eliminate dependence on imported oil.

Furthermore, hydrogen produced by the H_2Gen's HGM natural gas reformer at the fueling station or fleet operator's garage would cost less per mile than taxed gasoline. We estimate that the life-cycle costs of owning and operating a hydrogen FCV would be $2,290 *less* than owning and operating a conventional gasoline car as shown below, even though the FCV cost $2,800 more initially. This savings would increase to $3,260 over the life of the car if the auto companies succeeded in lowering their fuel cell system costs to $20/kW. *But this FC cost reduction is not necessary to achieve life-cycle cost savings over gasoline cars.*





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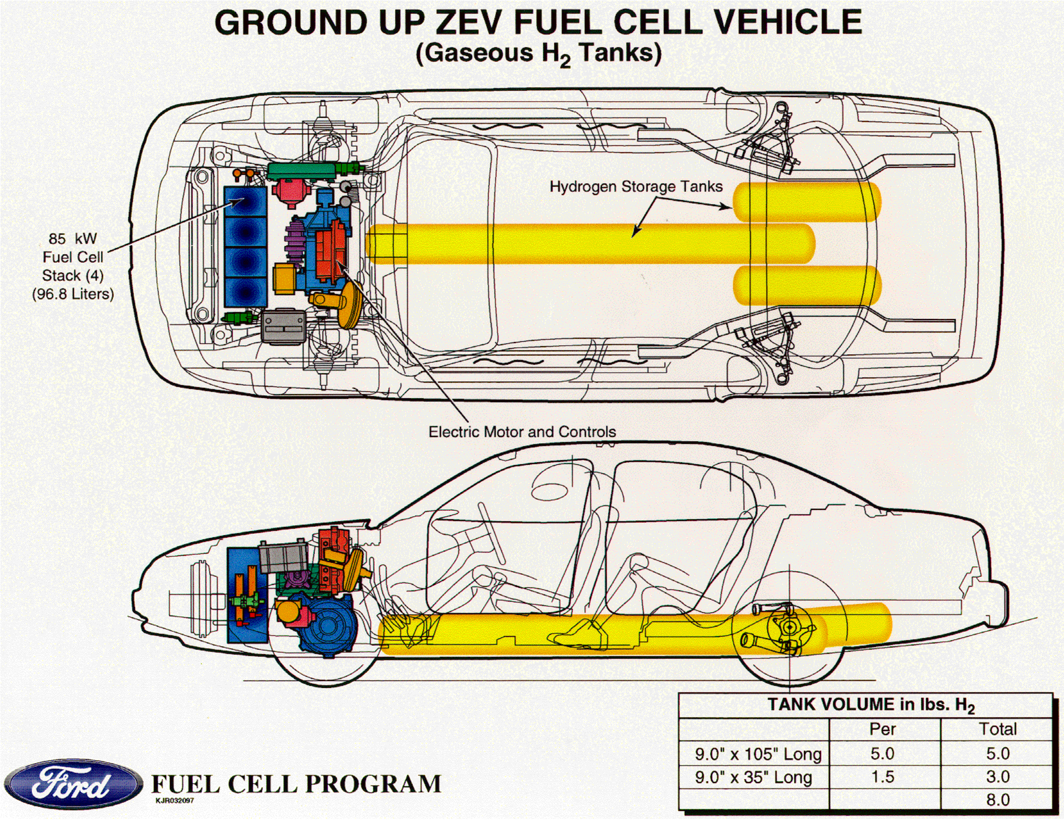
Even hydrogen made from renewable ethanol would be only slightly more costly on a life-cycle basis, costing the owner approximately $2,111 more over the life of the car.

#2) Hydrogen Storage

Joe Romm claims that a storage breakthrough is required before FCVs will be practical.

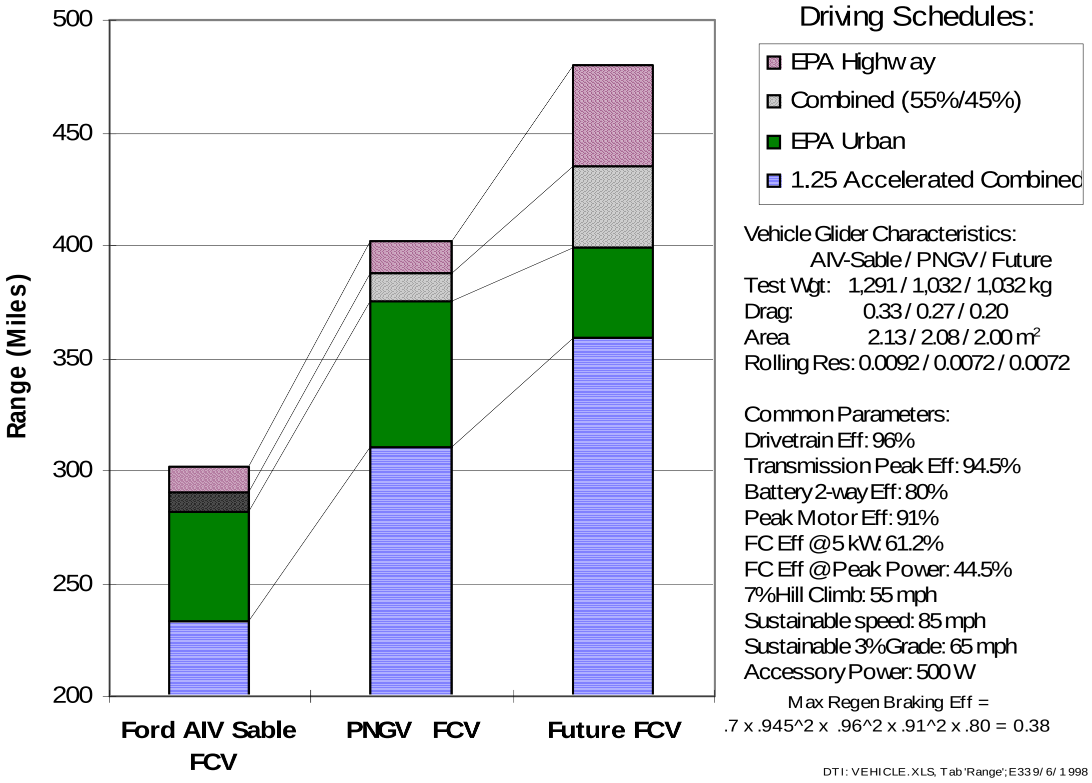


TANK VOLUME in lbs. H_2

	Per	Total
9.0" x 105" Long	5.0	5.0
9.0" x 35" Long	1.5	3.0
		8.0

The Ford Motor Company designed (but did not build) a FCV in 1994-95 that would have achieved 280 miles range using 5,000 psi hydrogen tanks based on a slightly modified Ford Contour, and 380 miles range with PNGV body parameters. Storage improvements would be welcomed, **<u>but no storage breakthrough is required</u>**.

[Ref: C.E. Thomas, B. D. James, F. D. Lomax, Jr., & I. F. Kuhn, Jr., “Fuel options for fuel cell vehicles: hydrogen, methanol or gasoline?” *Int. J. of Hydrogen Energy*, 25 (2000) p. 551-567.]



DTI: VEHICLE.XLS, Tab 'Range'; E33 9/6/1998

#3) Safety

Joe's bullet points on hydrogen safety:

- An unusually dangerous fuel
- Very leaky
- Odorless (probably unfixable)
- Invisible and burns invisibly
  ("A broom has been used for locating small H2 fires")
- Highly flammable (cell phone, lightning)
- Hence: onerous codes and standards
- HYDROGEN SELF-COMBUSTS!

His book is actually more balanced than these bullet points. He gives the full Addison Bain discussion to dismiss the Hindenburg accident (the outer cloth covering of the Hindenburg was coated with cellulose acetate filled with aluminum powder, a good rocket fuel, which most likely was ignited by static electricity from lightening in the area at the time of the landing in Lakehurst, New Jersey), and he notes that hydrogen has some positive safety attributes. But in person he emphasizes the negatives.

The "hydrogen self-combusts" is probably indicative of his extreme public pronouncements, ignoring the fact that oxygen and an ignition source are required for combustion of hydrogen!

Here are some quotes from the executive summary of the Ford Motor Company hydrogen safety report to the DOE:

> **"In normal operation, a hydrogen-powered fuel cell vehicle and dispensing system, with proper engineering, should be as safe as a gasoline, natural gas, or propane vehicle system."**
>
> **"In a collision in open spaces, a safety-engineered hydrogen FCV should have less potential hazard than either a natural gas vehicle or a gasoline vehicle…"**
>
> **"If we consider the total fuel system, including hydrogen production, transportation, storage and dispensing, the total public *exposure* to fuel risks could be less than those of the existing gasoline fuel infrastructure."**
>
> **"Overall, we judge the safety of a hydrogen FCV system to be potentially better than the demonstrated safety record of gasoline or propane, and equal to or better than that of natural gas."**

[Ref: "Direct Hydrogen Fueled PEM Fuel Cell System for Transportation Applications: Hydrogen Vehicle Safety Report," prepared for the U.S. Department of Energy, Office of Transportation Technologies by the Ford Motor Company, Dearborn, Michigan, Report DOE/CE/50389-502, May 1997.]

#4) High fueling cost.

Joe states that hydrogen from methane or the grid would cost $4 to $8+ per gallon of gasoline equivalent. He quotes an unreferenced Shell statement that “At the end of the day, hydrogen and other alternative fuels will be three to four times as expensive as oil-based products, and if no one wants to pay for that, we can’t make those fuels.”

Probably the best rebuttal comes from the National Research Council/ National Academy of Sciences 2004 report that Joe has quoted from on other subjects more in line with his conclusions.

The NRC report provides the following data on fuel economy and fuel cost for hydrogen produced at the fueling station by reforming natural gas; the cost per mile can then be readily calculated from the NRC data (last row):

	ICEV	HEV	FCV	
Fuel economy in 2015 (p. 6-16)	24 mpg	34 mpg	58 mpkg	
			Current	Optimistic
Fuel Cost /gallon or kg	$1.80/gal	1.80/gal	$3.51/kg (Table E-5)	$2.33/kg (Table E-36)
Fuel Cost (cents/mile)	8.3	5.9	6.1	4

The NRC report does state in one chapter that “the cost of generating hydrogen with any of the distributed technologies…would greatly exceed the gasoline costs.” [p. 5-7]. However, they neglect the increased fuel economy of the FCV that will reduce the costs per mile, the only figure of merit of importance to the driver. The last row of the above table calculates the actual costs per mile, using the NRC data, showing actual costs to the driver will be less.

Conclusion: **Data provided in the NRC report show that the cost of hydrogen per mile driven will be between 27% to 52% <u>lower</u> than the cost of gasoline at $1.80/gallon in a conventional car, and between 3% more to 32% less than the cost of gasoline used in a hybrid electric vehicle**[1].

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[1] Of course the $1.80/gallon for gasoline includes an average of 43 cents/gallon of highway tax, while the hydrogen is untaxed. We maintain hydrogen would not be taxed initially as a super-clean fuel. But even if we include the highway tax, the cost of hydrogen of roughly 2 cents/mile attributed to the gasoline ICEV,

5) Limited H2 stations: chicken & egg problem.

Joe quotes Argonne estimates of $600 billion for a hydrogen infrastructure and Shell estimates of “hundreds of billions of dollars”. He states (without reference) that Shell claims hydrogen infrastructure will cost $5,000 per car initially.

Using $500,000 for an HFA-2000 that could support 160 FCVs, the initial cost would be “only” $3,125/FCV. For an HFA 10,000 selling at $700K supporting 800 cars, the cost per car supported would be $875. We would expect further cost reductions with mass production of the hydrogen fueling appliances.

Byron McCormick of GM estimated in September 2003 that 11,700 hydrogen fueling stations could provide hydrogen to 70% of the US population in the 100 largest cities, within less than 2 miles of their homes, plus stations every 25 miles on the interstates connecting those 100 cities. They estimate a total cost per station of $1 million to provide 100 kg/day[2], enough to support 1 million vehicles nationwide. The total infrastructure cost to get started is therefore only $11.7 billion (GM states the cost as $10 to $15 billion). Additional stations would be added later, and the capacity of these early stations would need to be increased over time, but GM points out that those additions would be profitable and investments would be made on the economic basis of return on capital.

Conclusion: **GM estimates that an initial nationwide hydrogen infrastructure to support 1 million FCVs and to place a hydrogen fueling pump within 2 miles of the homes of 70% of the US population as well as every 25 miles on the interstates connecting the 100 largest cities would cost between $10 billion and $15 billion.**

[Ref: J. Byron McCormick (Executive Director, Fuel Cell Activities, General Motors), *Hydrogen: “The First Step” Transition to the Vehicles of Tomorrow*, presented to the Hart World Fuels Conference, Washington, D. C. 22 September 2003.]

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the future price hydrogen at 4 cents/mile + 2 cents/mile tax = 6 cents/mile would still be less than an ICEV an approximately equal to the fuel cost (including road taxes) of the HEV. Note that this calculation assumes that the FCV highway tax would be per mile to raise the same revenue, and not per MBTU or per gallon of gasoline equivalent. This implies that the government would provide no long term incentive to switch to cleaner fuels by raising highway tax revenues by some other mechanism (like gas guzzler taxes).

[2] The H_2Gen factory-built HGM hydrogen generator module that produces 113 kg/day costs $280,000 in single quantities. Adding compression to 7,000 psi to fill 5,000 psi hydrogen tanks on FCVs plus storage and a dispenser would raise the price to about $560,000 per station, well below the GM estimate of $1 million per station.

#6) Hydrogen won't be clean until 2035.

Joe claims that hydrogen from Shell would generate 30% more CO_2 and 200% higher NOx than using gasoline in a 2004 Prius! This must be based on electrolytic hydrogen. Again quoting the (supposedly critical) NRC report is the most effective rebuttal to Joe's statements.

a) For CO_2, the NRC report estimates that hydrogen from natural gas made at the fueling station (the only likely cost-effective option in the first few decades) used in a FCV will produce 3.31 kg of carbon per kg of hydrogen. (Figure 5-9, page 5-29) They also show a bar labeled "Gasoline (GEA)", where GEA = gasoline efficiency adjusted, with an adjusted carbon emission of 5.1 kg of carbon per kg of hydrogen equivalent. There is no explanation of how this GEA is calculated on page 5-29, but the reader has to go back to page 5-13 to see that this is based on a gasoline HEV, not a standard gasoline ICEV. The equivalent carbon emissions on the scale used on page 5-29 for a conventional car would be 7.55 kg of carbon/kg of hydrogen for the ICEV.

The following table converts the NRC data to grams of carbon per mile:

	ICEV	HEV	FCV	
Fuel economy in 2015 (p. 6-16)	24 mpg	34 mpg	58 mpkg	
			Current	Optimistic
Carbon emissions (kg/gal or kg/kg of H2)	3.0 kg/gal (pg. 5-13)	3.0 kg/gal	3.31 kg/kg (pg. 5-39	2.82 kg/kg (pg. 5-30)
Carbon emission (grams of carbon/mile)	130	88	57	49
Carbon Reductions relative to ICEV	0	-32%	-56%	-63%

Conclusion: **Based on the NRC report, a hydrogen-powered FCV with hydrogen produced at the fueling station from natural gas would reduce well-to-wheels carbon emissions by 56% to 63% immediately compared to a conventional gasoline car. In addition, a FCV would cut carbon emissions by 35% to 45% compared to a gasoline HEV.** Hence each hydrogen FCV put on the road will begin reducing carbon emission immediately …we certainly do not have to wait until 2035.

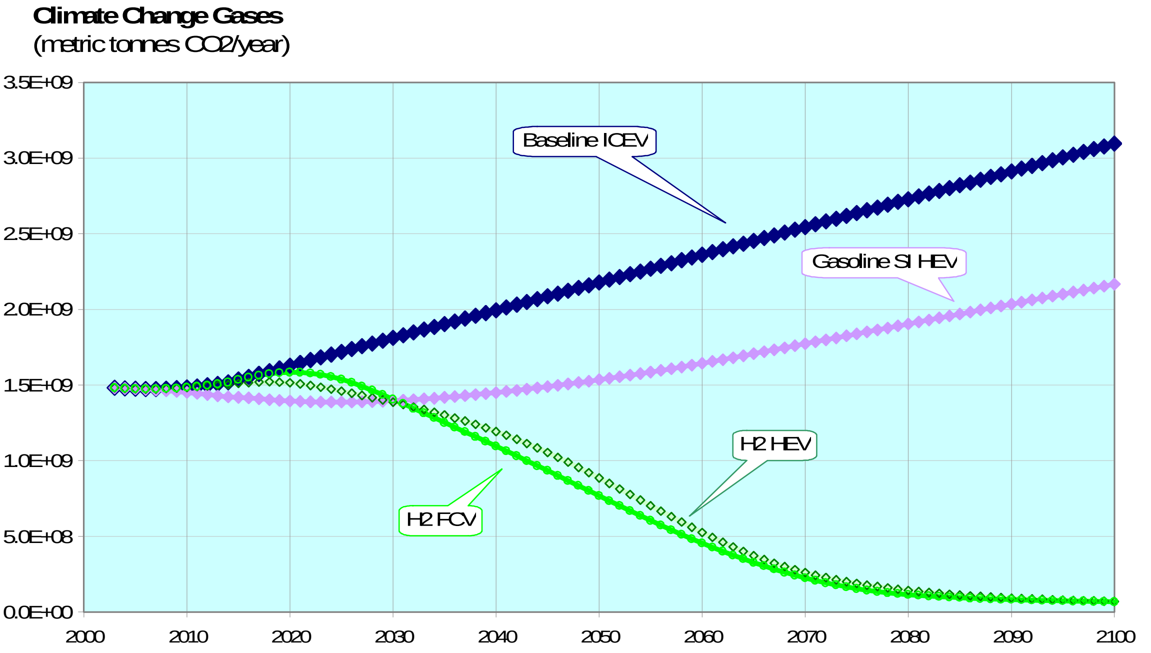
b) NOx emissions will be zero from the vehicle, and negligible from an on-site SMR such as the H_2Gen HGM, since the reformer operates below the NOx formation temperature. An increase in NOx emissions is not credible. Even in the case of electrolysis of water that generates NOx back at the electrical power station, in most cases these emissions will be outside the urban airshed, and will not contribute to photochemical ozone formation in the EPA non-attainment areas, the reason for cutting back NOx emissions in the first place.

#7) Hybrid competition.

Here are Joe’s bullet points comparing the Toyota Prius with a FCV:

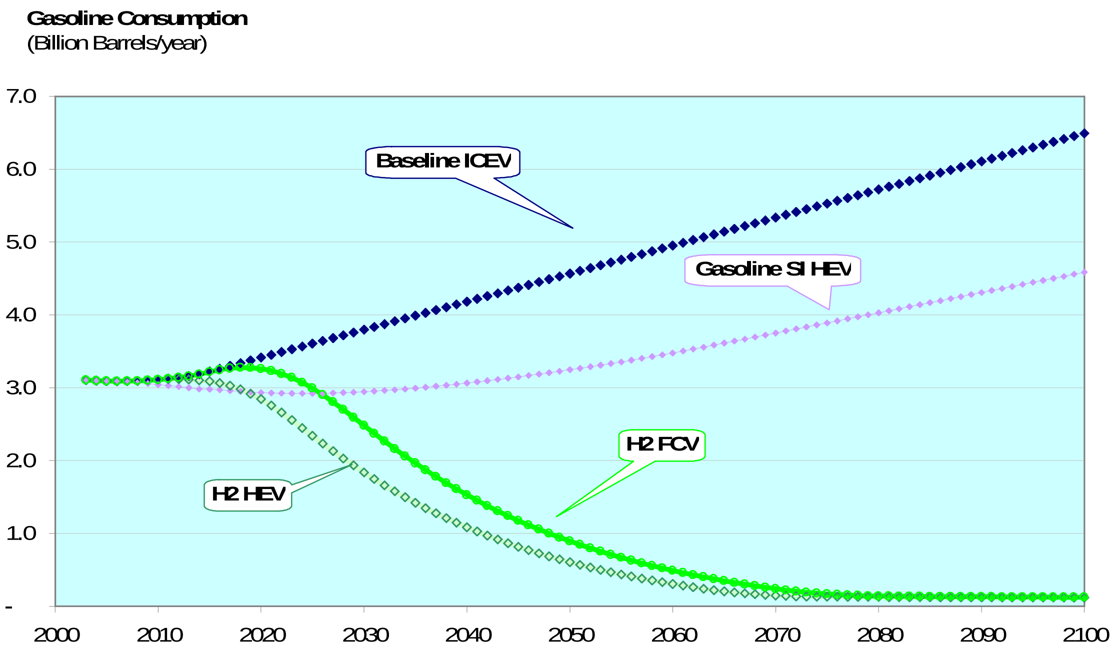
- Will cost more ($20,000+)
- 3X+ annual fuel bill (5X+ for green hydrogen)
- Limited fueling options
- Major safety and liability issues
- NOT greener
- Likely through 2025 if not much longer

First, we have no debate with Joe’s admiration of the gasoline hybrid electric vehicles (HEVs) such as the Prius. In the short term, everyone should be encouraged to purchase HEVs to cut oil imports and pollution. It is not a question of either HEVs or FCVs; we can do both.



H2Gen: H2 ICE HEV.XLS; Tab 'Annual Sales';BF 27 4/25 /2004

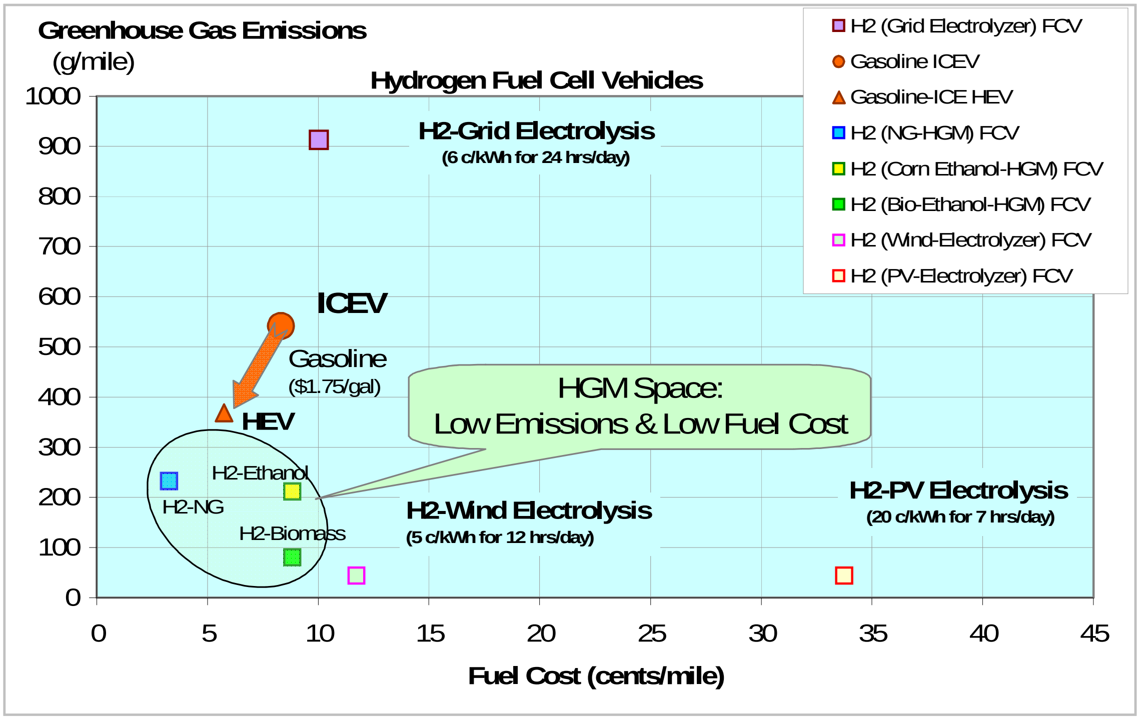
In the long term, however, the gasoline HEV is a dead-end road for both GHGs and oil import reductions. The graphs below show the results of some computer modeling we have conducted, showing that gasoline HEVs will temporarily reduce GHGs and oil imports, but that advantage is wiped out within a decade or so by increased vehicle miles traveled (VMT). Hence we have to move to hydrogen to assure a long-term solution to GHGs and oil imports. These charts assume that all hydrogen is made from natural gas initially, gradually transitioning to hydrogen from renewables, such that 50% of all hydrogen comes from renewables by 2050. We have included hydrogen-powered ICE HEVs (the Prius running on hydrogen instead of gasoline) in this simulation, with the assumption that they could enter the marketplace before FCVs.



H2Gen: H2ICE HEV.XLS; Tab 'Annual Sales';BR 29 4/25 /2004

Conclusion: **Gasoline HEVs will provide only a temporary reduction in GHG emissions and oil imports, as increasing vehicle miles traveled eventually cancel out the improved fuel economy of HEVs, and pollution and oil consumption rise inexorably thereafter. Hydrogen made initially from natural gas and transitioning to renewable hydrogen over the next few decades provides the only option for permanently decreasing GHGs and oil imports. Furthermore, hydrogen-powered ICE HEVs like the Prius could provide an interim transition to fuel cell vehicles that would substantially reduce GHGs and oil imports. *We do not have to wait for fuel cells to begin reaping the benefits of the hydrogen economy.*** Joe Romm did not consider this realistic alternative, even though we did brief him on the concept while he was writing his book.

We have also estimated the fuel cost and GHG emissions for hydrogen made from ethanol by an HGM at the fueling station to supply hydrogen to FCVs. As shown below, hydrogen from ethanol could be nearly cost competitive with gasoline in ICEVs, with the potential for greatly reduced GHGs in the near term. GHG emissions would be substantially reduced if the ethanol were made from the corn stover (stalks and roots) cellulose instead of just the grain. The cost of hydrogen made by electrolyzing water from wind electricity and particularly from PV electricity is much greater today. We conclude that hydrogen made from ethanol is the best near-term option to begin the transition to a sustainable hydrogen economy today.



H2Gen:Ethanol vehicles.XLS; Tab 'GHG vs Fuel Cost';T 114 5/30 /2004

Conclusion: **Hydrogen can be made from natural gas at the fueling station at lower cost per mile driven and with lower GHG emissions than with gasoline in conventional cars as well as with gasoline-powered hybrid electric cars such as the Prius. Hydrogen made from ethanol at the fueling station is cost competitive with gasoline in conventional cars, with the potential for dramatically reduced GHG emissions as ethanol production shifts from using only the corn kernels to full cellulose utilization**.