

# **Viable and Sustainable Energy Strategies Grounded in Source-to-Service Analyses**

*A Perspective of the Role of Fuel Cells in Transportation*

**Jan H. J. S. Thijssen**

J. Thijssen, LLC  
4910 163<sup>rd</sup> Avenue NE  
Redmond, WA 98052 / USA  
jant@jthijssen.com

## **Abstract**

The current debate about sustainable transportation increasingly focuses on hydrogen fuel cell vehicles (H2FCVs). While the ultimate vision of a solar-power-to-H2FCVs has obvious appeal, other options could provide at least the same long-term benefits and will start to provide benefits much sooner. In addition, fresh thinking about the role of fuel cells in future powertrains could lead to more attractive vehicles for drivers, facilitating their introduction. The following considerations should inform R&D planning for powertrain and power technology development programs for both industry and government.

## **Introduction**

In the past five years, considerable governmental and industrial investment in fuel cell development has focused the debate about sustainable transportation systems increasingly on hydrogen fuel cell vehicles (H2FCVs) as THE solution. The ultimate vision of emission-free H2FCVs using an entirely renewable fuel (hydrogen from solar, or wind energy for example) is obviously appealing to the public. Automakers would like to see H2FCVs disassociate air pollution from its products in the minds of their customers and government regulators.

However, the tremendous hurdles that H2FCV developers face have been well-identified and discussed extensively: fuel cells must become more reliable, cheaper, and smaller; compact, lightweight and affordable hydrogen storage solutions must be found; a hydrogen infrastructure must be established; and safety issues must be addressed to avoid roadblocks to the use of H2FCVs. Overcoming these hurdles will require the development of new materials (catalysts, membranes), new technologies, and time (proponents think technology development will take another ten years, and establishment of a hydrogen economy 20 – 50 years).

A number of alternatives under development could provide similar benefits, and could be introduced sooner. Automakers are developing hybrid vehicles and the EU is promoting the use of alternative fuels. These options are equally worth exploring. Numerous studies have outlined the myriad combinations of primary energy resources, energy carriers, and powertrain technologies. Practically however, most of these options carry a significant additional cost without providing significant benefits

directly to the driver. Considering this situation, there are several possible ways forward:

- Carefully analyze the trade-offs between the options, identify the ones that provide the desired long-term benefit, then use government instruments to realize the most cost-effective one of these (e.g. catalytic converters);
- Continue R&D of several options until cost and performance are acceptable (passenger diesel in Europe);
- Try to identify ways to provide real benefits to the driver (new features, amenities) that are enabled by the (more) sustainable options.

In this paper we will try to identify if and how fuel cells may play a role in providing viable energy strategies for transportation. We will compare the potential societal benefits that various alternative fuels and powertrain technologies may provide as well as their attractiveness to drivers and fuel suppliers. Also, we focus on long-term impacts and trade-offs (not transitional issues), light-duty vehicles (not heavy-duty vehicles or stationary energy applications).

## **Society's Goal: A Sustainable, Secure Energy Strategy**

### ***Local Air Pollution***

H<sub>2</sub>FCVs and battery electric vehicles (BEVs) will have zero emissions of common air pollutants. H<sub>2</sub>FCVs would thus completely remove emissions control considerations from the transportation system. Tests and analysis of liquid-fueled FCV reformers have indicated that liquid-fueled FCVs too would provide a significant reduction in emissions from current levels [3]: NO<sub>x</sub> emission levels around 0.01 g/km at steady state and significant levels of non-methane organic hydrocarbons. Start-up would significantly increase drive-cycle emissions though quantification is difficult still.

However, new regulations continue to push down emissions from conventional powertrains based on internal combustion engines (ICEs), reducing NO<sub>x</sub> emissions to about 0.05 g/km and particulate matter emissions to about 0.007 g/km [1, 2]: roughly 90% reductions from current values (somewhat less in the EU). As a consequence, the emissions-benefits of FCVs are reduced, and the urgency of emissions-reduction from vehicles is reduced. In fact, liquid-fueled FCVs may not have much of an emissions-advantage over advanced SI-based vehicles.

### ***Energy Use and Greenhouse Gas Emissions***

H<sub>2</sub>FCV and advanced diesel hybrid (CIHEV) technologies could reduce source-to-service energy consumption from US midsize vehicles by 40 – 60% (Figure 1). As reported by others [4-12], in the source-to-service analysis the high on-board efficiency of the H<sub>2</sub>FCV is off-set by the relatively low efficiency of hydrogen production and transport (including compression or liquefaction). We base our analysis on the energy conservation principle and use the true energy content (HHV) of chemical carriers for the comparison with all-electric solutions. While the bars bracket the plausible range of outcomes, they do not represent a proportional indication of technical risk. In addition to the powertrain impacts found here, other

changes in vehicle design (e.g. weight reduction, streamlining, and intelligent controls) may reduce energy consumption by another 10-30% [9].

Notwithstanding this impressive reduction potential at the vehicle level, alternative fuels or resources will be required to achieve sustainability (even with modest vehicle population growth rates, a more than 85% reduction in per-vehicle energy consumption will be required to bring total energy use down to affordable levels by the end of the century). In addition, conventional fuel production pathways are already highly efficient.

The differences between options are emphasized in the GHG comparison as the effect of the carbon content of the alternative fuels and resources compounds with the source-to-service energy efficiency. Although, on account of the somewhat lower carbon intensity of natural gas, natural-gas-based H<sub>2</sub>FCV combination have slightly lower GHG emissions, they are only marginally lower than those from advanced CI-engine-based vehicles. If desired, CO<sub>2</sub> could be sequestered in some natural gas based H<sub>2</sub>FCV options, further reducing GHG emissions from such systems. However, using a renewable energy carrier can virtually eliminate greenhouse gas emissions, independent of the powertrain it is used in.

### **The Driver's Perspective: Vehicle Utility and Cost**

The success of new fuels and vehicle technologies hinges on driver and industry acceptance. Utility (in the broadest sense of the word) and cost are the most important factors in choosing a vehicle. Utility, in this context, encompasses performance attributes (payload or passenger capacity, acceleration, top speed, range), comfort (noise, vibration, harshness, smoothness of ride), convenience (e.g. of refueling), and even image. The importance of each of these factors varies dramatically from market segment to market segment.

Drivers and owners are willing to accept substantially higher prices (e.g. higher-performance engine, on-board entertainment system, GPS tracking system), while reduced utility must be accompanied by substantial (e.g. more than 10-20%) cost reductions in order to be accepted (compare introduction of CNG and methanol with that of diesel in Europe). Especially for passenger cars and SUVs, image is also a very important factor in buying a vehicle (in market surveys fuel economy reportedly routinely ranks number twenty or lower).

Unfortunately, many alternative fuels and powertrain technologies are not (or cannot be) presented as providing either better utility or significant cost advantages to the driver. These factors, it turns out, discriminate the powertrain and fuels technologies with respect to their viability.

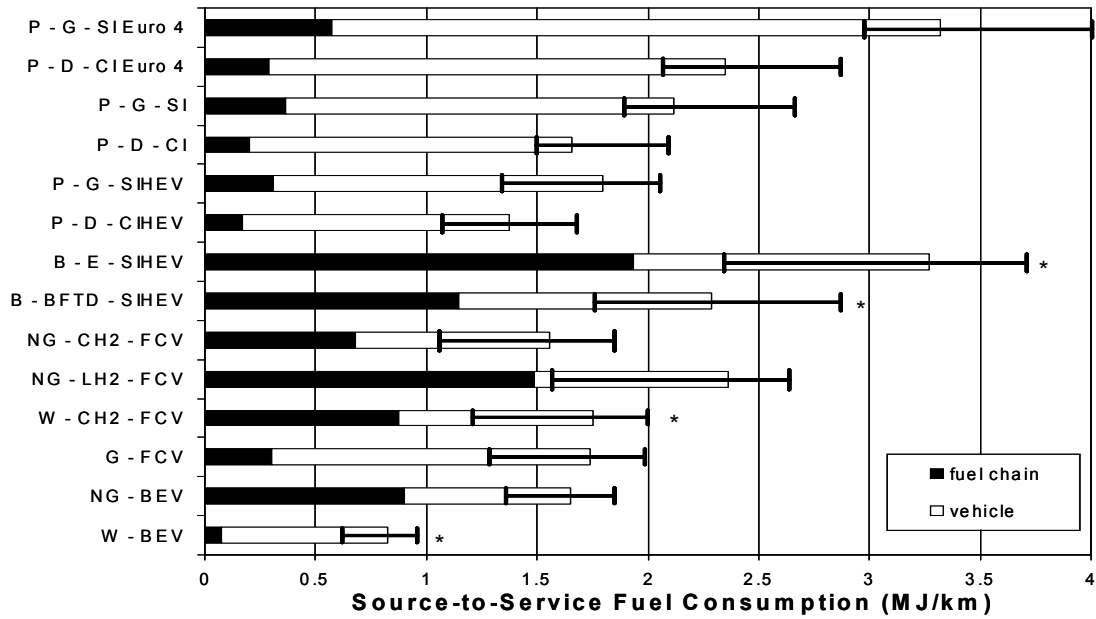
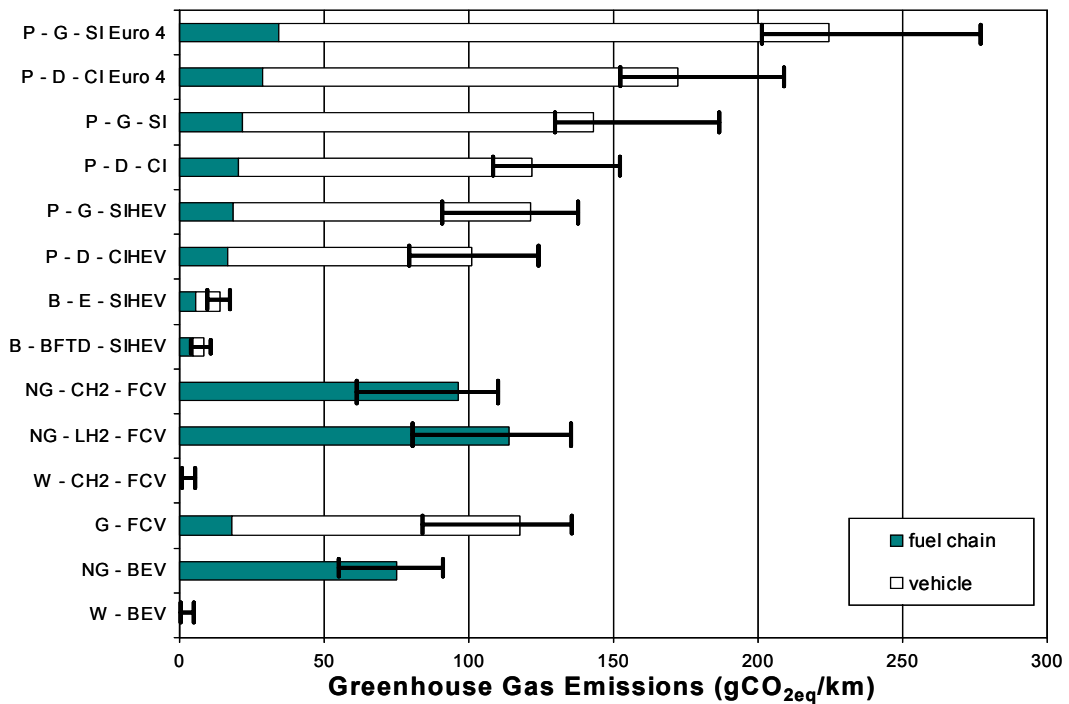


Figure 1a Vehicle and Source-to-Service Fuel Consumption based on Higher Heating Values (HHV) of all Chemical Energy Carriers



Resources: P = Petroleum; B = Biomass; NG=Natural Gas; W = Wind; GT = Natural Gas Turbine; \* = renewable  
 Energy Carriers: G = Gasoline; D = Diesel; E = Ethanol; BD = Bio Fischer-Tropsch Diesel; CH2 = Compressed Hydrogen; LH2 = Liquid Hydrogen; E = Electricity  
 Powertrains: SI = Spark Ignition; CI = Compression Ignition; SIHEV = Spark Ignition Hybrid Electric ; CIHEV; Compression Ignition Hybrid Electric; FCV = Fuel Cell; BEV = Battery Electric

Figure 1b Greenhouse Gas Emission for Various Fuels and Powertrain Technologies (Sources: [5, 6, 10, 12]).

## **Vehicle Utility**

To the extent possible, vehicle performance factors such as performance and range will be engineered for alternative fuel or advanced powertrain vehicles to meet customer demands. However, some essential differences in powertrain characteristics will have an impact on overall vehicle characteristics. Advanced CIHEV and SIHEV vehicles will tend to perform and look more or less the way conventional vehicles do, as the core of their drivetrain is still the ICE engine and mechanical transmission. Performance, weight, and size will be about the same. Noise may be slightly reduced eventually, and of course range may be much improved. Fuel cell vehicles on the other hand will have several distinct characteristics:

- H2FCVs will be quieter than ICE vehicles (once quiet blowers / compressors have been developed), and provide better low-end torque;
- H2FCVs will be able to provide very high efficiency idle or APU power. This could appeal e.g. to users who want to leave a refrigerator or AC running while parked;
- FCVs will likely be larger and heavier. The fuel cell itself, its supporting systems, and the fuel tank (in the case of H2FCVs) all contribute to a weight that is currently projected to be about 50% higher for a typical 75 – 100 kW engine (more for larger capacities). This compromises passenger / payload capacity, performance, and fuel economy. New materials and technology concepts will likely be needed for a breakthrough in this area;
- FCVs will likely be more sensitive to environmental conditions (temperature, humidity). For G – FCVs the impact of start-up energy requirements will make them less suitable for very short trips. New anode catalysts and other materials may be needed to address this problem;

## **Infrastructure**

In addition, there are various infrastructure implications of the fuel and vehicle choice. For the vehicle, the implications are mainly limited to setting up a properly trained service network (needed for all new powertrain technologies) and recycling systems for any non-fuel consumables (such as catalysts).

For the fuel, the degree of infrastructural change depends strongly on the fuel choice. The implications have been discussed in detail elsewhere [13] and will not be repeated here, except to state that:

- Implementation of a hydrogen infrastructure faces a number of issues, including safety issues, real estate issues, temporary infrastructure utilization, driver concerns over fuel availability. Change to a hydrogen infrastructure must go hand-in-hand with introduction of H2FCVs;
- Bio-ethanol and bio FT diesel can be introduced first as a blending component in conventional gasoline and diesel (up to 10% and 30% respectively without any impact on vehicles, then requiring minor service). Introduction of these fuels can be planned gradually and more-or-less independently from the introduction of the corresponding vehicles.

## Vehicle Ownership Cost

The biggest hurdle to the implementation of almost all alternative fuel and advanced powertrain technologies is the higher cost. Although the distribution varies somewhat with the type of vehicle, the powertrain depreciation cost is the largest of the powertrain-related costs, followed by fuel and maintenance.

*First Cost.* Though it is extremely difficult to project cost of future technologies in mass-production, a number of careful studies suggest (Figure 2) that, while the additional cost for advanced ICE and ICE-hybrid technologies may be incremental (adding less than 10% in high-volume production), the additional cost of H2FCVs could add about \$5,000 (or about 40%) to the cost of the vehicle. While there is considerable uncertainty about the cost of H2FCVs (given that current technology doesn't yet provide all necessary functionality) the detailed cost studies quoted here have relatively optimistic assumptions about fuel cell performance (essentially assuming that currently demonstrated peak performance can be sustained for the life of the vehicle without cost or functionality compromises), leaving little hope for significantly lower cost absent additional technology breakthroughs.

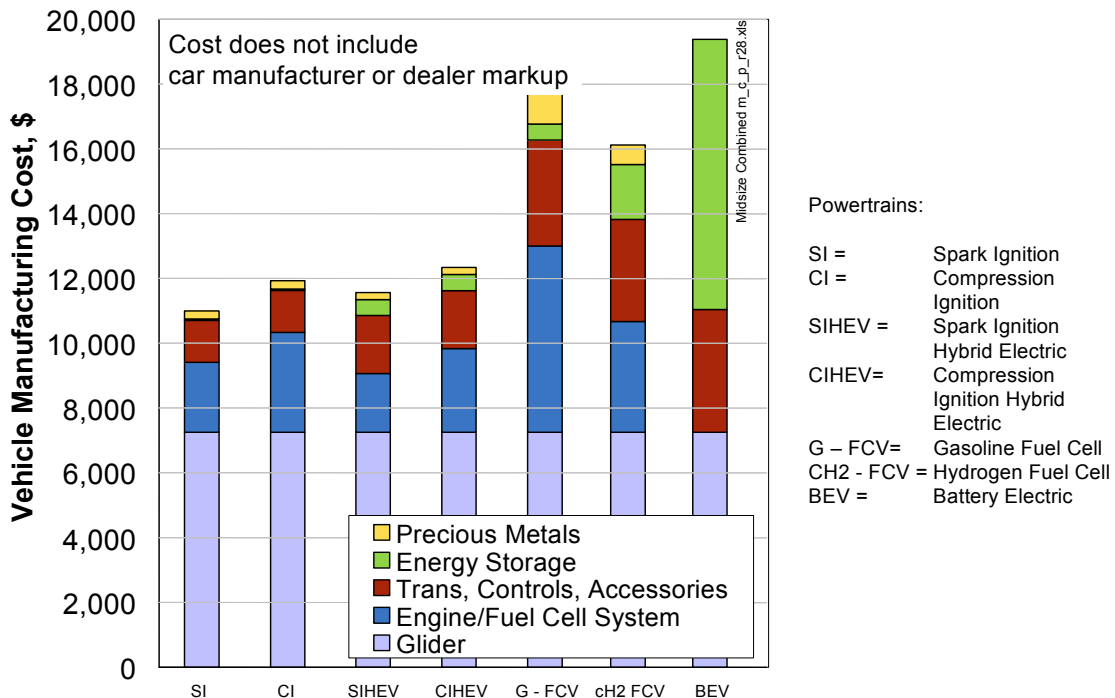


Figure 2 Comparison of Powertrain Costs for Current and Future LDV Powertrains (Source: [6])

It is also important to understand that most of the studies are done for mid-size cars. So far as the author knows, little effort has gone into adapting H2FCV technology to high-end vehicles; the market segment into which powertrain technologies are usually introduced first.

Several key factors contribute to the high cost of H2FCVs:

- The basic fuel cell components (the cells) are expensive due to the high cost of the catalyst (noble metal) the electrolyte membrane, the catalyst supports, and the interconnects;
- A considerable number of balance-of-plant components support the fuel cell stacks;
- Hydrogen storage systems range from 20 times (compressed storage) to 500 times (metal hydride storage) more expensive than liquid fuel tanks.

As with the weight and volume issues, improving H2FCV cost will require fundamental technology improvements (Such as the development or discovery of better materials).

### **Operating Cost**

There is a wide spread in the cost of alternative fuels and most are considerably more expensive than conventional gasoline and diesel. Alternative fuels can be categorized into three cost groups. Some fossil-based alternative fuels such as FT diesel and methanol might be supplied at prices similar to those of ultra low sulfur diesel and gasoline. The lowest-cost bio-based fuels can be produced and distributed for roughly twice the cost of gasoline and diesel (Assuming oil prices around \$20 - \$25 per barrel, see Figure 3). Hydrogen will likely cost about three times or more the price of gasoline or diesel. If the hydrogen is to be manufactured based on wind-power electrolysis (or hydro or nuclear power) cost will be five to eight times more costly (solar-power would cost even more). A quick look back at Figure 1 shows that the H2FCVs superior fuel economy doesn't make up for these higher fuel costs, even especially compared with future HEV technology.

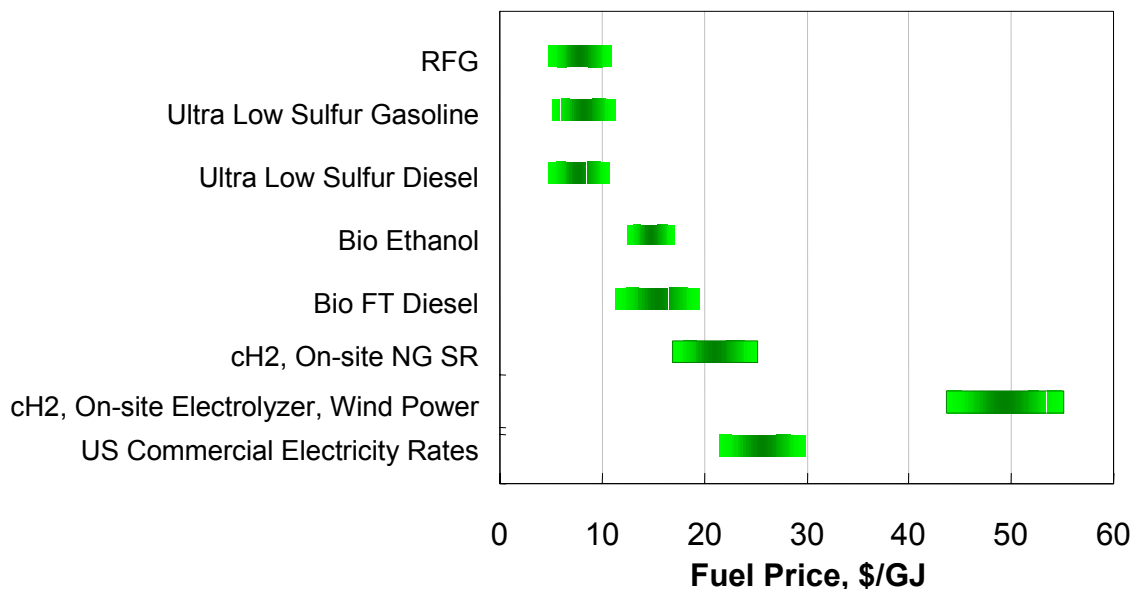


Figure 3 Typical Projected Fuel Cost Ranges for Various Motor Fuels (Source: [6])

Maintenance costs represent a major uncertainty for both hybrids and especially for FCVs. Currently, the operating life of the fuel cell stacks falls far short of the

requirements (around 1,000 to 2,000 hrs vs required 5,000 – 10,000 hrs or more). Improving stack life without further increasing cost represents a challenge for fuel cell stack developers. Unless fuel cell stack life and battery life are dramatically improved, long-term maintenance costs of H2FCVs will be far higher than that of any of the ICE options, but in the following we assume the maintenance cost of all technologies is equal.

### Cost-Effectiveness

The cost-effectiveness of improvements in sustainability is significantly better for the liquid-fueled approaches than for the H2FCV options. Now that we know the differences in benefits and cost we can determine the cost effectiveness of the options (i.e. improvement divided by the incremental cost). This approach also allows a comparison to the cost-effectiveness of non-transportation [11, 13]. Using this methodology with the data discussed in this paper, we get a very clear distinction categorization of the cost-effectiveness and impact potential of the options considered here (Figure 4).

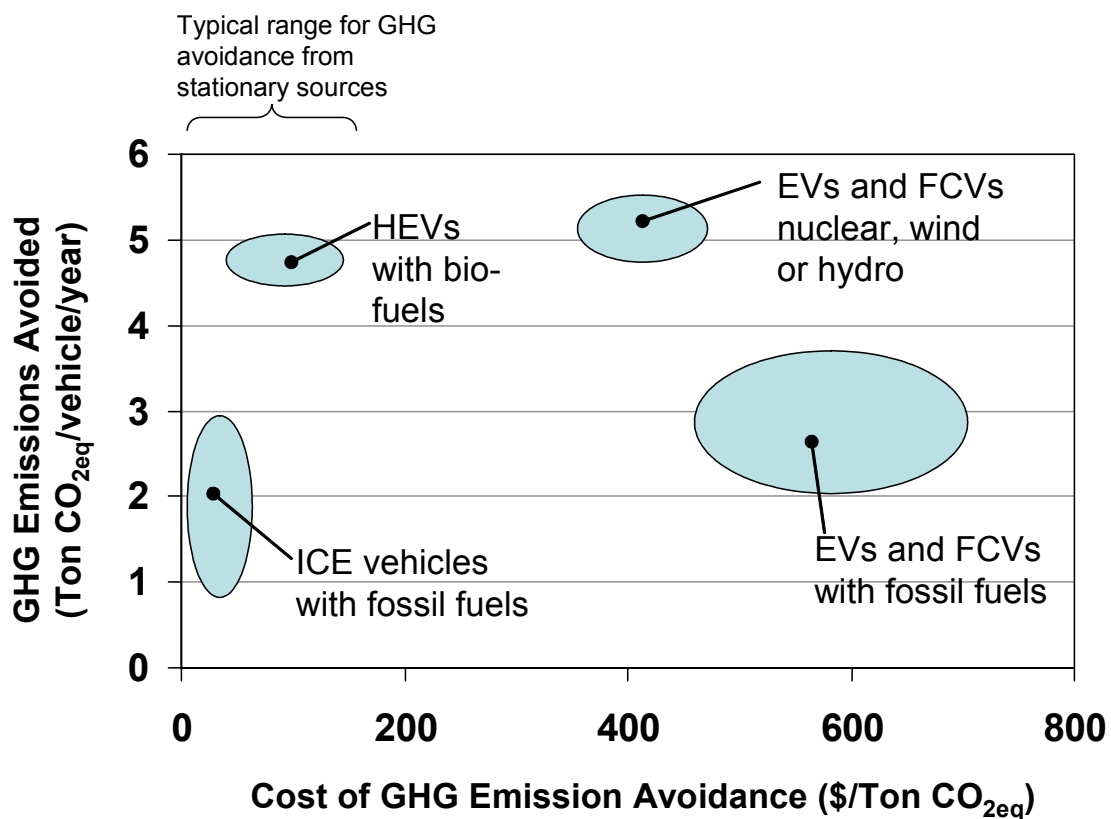


Figure 4 Impact Potential Compared with Cost of Emissions Avoidance.

A number of conclusions emerge from the analysis:

- FCVs offer more or less the same trade-offs in cost and greenhouse gas benefits as EVs (still FCVs would have better range than the EVs);
- Windpower-based H2FCVs and EVs provide more cost-effective GHG emission reduction than those based on natural gas;

- Advanced engine-based powertrains with biofuels offer almost the same benefits as FCVs and EVs, but at a about 20% of cost;
- The cost of CO<sub>2</sub> reduction with FCVs is several times higher than with advanced ICE vehicles and biofuels
- The big cost differential between H<sub>2</sub>FCVs and bio-fuel HEVs lies in the fuel cell powertrain, not in the fuel cost.

## **Increasing the Attractiveness of Fuel Cells for Vehicles**

If fuel cells were to provide significant added functionality to the driver, (some of) the additional cost might be acceptable. The continuous stream of new features and gadgets found in automobiles proves that drivers and owners are ready to pay more for new capabilities of their vehicles (on-board entertainment, GPS, etc). Some of the potential benefits that fuel cells could offer for vehicles could include:

- Always-on power capability (APU capability) that could, for example, allow AC or refrigerator operation while parked, or allow the vehicle to be used as an emergency or work-site generator;
- The FCV electric drive may allow low-cost implementation of four-wheel drive.

However, it appears unlikely that such benefits would justify the development of a completely new fuel infrastructure (never mind that it would offset some of the benefits by increasing fuel consumption) or the added \$5,000 manufacturing cost for a mid-size vehicle. The thought led the author to develop some alternative thoughts about the role of fuel cells in vehicles [14]. A small, liquid-fueled fuel cell (say a small SOFC) were integrated into the vehicle to provide low-speed motive power, APU service, and to drive electric ancillaries, while a simplified ICE engine meets high-power needs. Preliminary analysis indicates that a large SUV equipped with a 10 kW electric drive fuel cell with a 250 kW gasoline or diesel engine would get 75% of the benefit of a full H<sub>2</sub>FCV, and operate about 75% of the time on FC power only. It appears that the projected extra cost of about \$3,000 over the conventional gasoline version might just be acceptable for the extra functionality. The cost and energy performance would be similar that of a CIHEV but functionality and emissions performance would be superior.

## **Conclusions**

Analysis of our own studies as well as those carried out by others indicate that H<sub>2</sub>FCVs might provide significant advantages (provided successful technology development), similar to those that could be achieved with advanced SIHEVs and CIHEVs fueled with bio-fuel. The latter option appears to provide a more plausible path to a sustainable transportation system, with a gradual transition leveraging the existing infrastructure.

Given these results, it appears that in order to make H<sub>2</sub>FCVs an attractive proposition, a very large cost-reduction (E.g. to the same level as HEVs), and a push for ultra-high efficiency are key. This points to a need for emphasis on relatively fundamental science and technology development (E.g. in new materials) rather than

vehicle demonstration. I believe that governments and industry should consider these findings in (re-) structuring their R&D programs.

Focusing on providing added functionality, preliminary analysis indicates that hybrids between fuel cells and ICEs may prove to yield more attractive vehicles than simple FCVs or FC hybrids. Especially for high-powered vehicles such as large SUVs and luxury cars may benefit from the added functionality. Similar thinking may be needed in vehicle design in general.

## References

1. *Control of Air Pollution From New Motor Vehicles: Heavy-Duty Engine and Vehicle Standards and Highway Diesel Fuel Sulfur Control Requirements: Final Rule*, in 40 CFR Parts 69, 80, and 86. 2001.
2. Dixson-Decleve, S. *Global Automotive Fuel Quality and Fuel Quality Monitoring Trends*. in *CEN TC/19 Symposium on Automotive Fuels*. 2003. Amsterdam.
3. Fable, S. and S. Unnasch. *Fuel Cell Reformer Emissions*. in *DOE Hydrogen, Fuel Cells and Infrastructure Technologies Annual Review Presentation*. 2004. Philadelphia, PA, USA.
4. Edwards, R., et al., *Well-to-Wheels Analysis of Future Automotive Fuels and Powertrains in the European Context*. 2004, JRC/IES.
5. Group, A.F.C., *Report of the Alternative Fuels Contact Group*. 2003, Alternative Fuels Contact Group.
6. Thijssen, J. and S. Lasher, *Guidance for Transportation Technologies: Fuel Choice for Fuel Cell Vehicles*. 2002, DOE Office of Hydrogen, Fuel Cells, and Infrastructure Technology: Cambridge, MA, USA.
7. Unnasch, S. and L. Browning, *Refinement of Selected Fuel-Cycle Emissions Analysis*. 2000, California Air Resources Board Research Division: Sacramento.
8. Wang, M., *Well-to-Wheel Energy Use and Greenhouse Gas Emissions of Advanced Fuel / Vehicle Systems; North American Analysis*. 2001, Argonne National Laboratory: Argonne, IL, USA.
9. Weiss, M.A., et al., *On the Road to 2020; A Life-Cycle Analysis of New Automobile Technologies*. 2000, Massachusetts Institute of Technology, Energy Laboratory: Cambridge, MA, USA.
10. Weiss, M.A., et al., *Comparative Assessment of Fuel Cell Cars*. 2003, Massachusetts Institute of Technology, Energy Laboratory: Cambridge, MA, USA.
11. Auto-Oil, *A Technical Study on Fuels Technology Related to the Auto-Oil Programme*. 2000.
12. GmbH, L.-B.-S., *GM Well-to-Wheel Analysis of Energy Use and Greenhouse Gas Emissions of Advanced Fuel / Vehicle Systems; A European Study*. 2002, L-B-Systemtechnik GmbH: Ottobrunn, Germany.
13. Bosma, W.J. and J. Thijssen, *Analysis and Evaluation of GAVE Chains*. 1999, Novem, Netherlands Agency for Energy and the Environment: Utrecht, The Netherlands.
14. Thijssen, J.H.J.S., J.P. Mello, and J.R. Linna. *Cost Competitiveness of Fuel Cell Vehicles Through Novel Hybridization Approaches*. in *SAE World Congress*. 2003. Detroit, MI, USA: SAE, Inc.