An Affordable Hydrogen Transportation System

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ABSTRACT:
The end game is clear: hydrogen made from renewable energy and consumed in a fuel cell vehicle will eventually eliminate local air pollution, greenhouse gas emissions and dependence on imported fossil fuels. Getting from here to there is the challenge. How does society introduce affordable hydrogen fuel and affordable hydrogen vehicles in the near term to pave the way for a renewable hydrogen transportation system in the future?

We describe an affordable transition strategy based on hydrogen made initially from natural gas at the fueling station, transitioning over time to renewable hydrogen when and where it becomes cost effective, and based on hydrogen-powered internal combustion hybrid electric vehicles as surrogates for fuel cell vehicles until such time that FCV's become reliable and affordable. We show the costs, greenhouse gas emissions and oil import dependency over a 100-year transition to the renewable hydrogen future. We conclude that making this incremental on-site hydrogen fueling infrastructure transition will cost less than the costs of maintaining the existing gasoline infrastructure system.

KEYWORDS: renewable hydrogen, hydrogen hybrids, affordable transition

Introduction

Across the globe, people share the same aspirations for minimizing local air pollution, curbing greenhouse gas (GHG) emissions, minimizing resource depletion, and reducing dependence on imported fossil energy. These aspirations are of great importance both in industrialized economies and in nations now in the midst of rapid transition and economic growth. We believe that hydrogen, used as a fuel for transportation, will ultimately prove the superior means of allowing nations to realize these aspirations. But we also believe that there must be practical, cost efficient ways to provide hydrogen to the transport sector – not only in the long run, but especially during the transition to this future. If we don't have an economic solution for the transition, fuel cell and hydrogen transportation will not gain the commercial popularity essential to become the long run solution to our pollution, greenhouse gas and national security problems.

The Renewable Hydrogen End Game

Those advocating a shift to hydrogen as the main energy carrier for the transportation sector can clearly visualize the end point: hydrogen will be generated by electrolysis of water using renewable electricity sources such as photovoltaics, solar thermal electricity, wind turbines, geothermal and hydroelectricity, and it would also be produced by reforming biomass including alcohols made from agricultural crops, from municipal solid waste, landfill gas or coalbed methane. This hydrogen would be consumed in zero-emission fuel cell vehicles (FVCs) for ground transportation and would be burned directly in jet airplanes. Operating such a renewable hydrogen transportation system would produce no local air pollution, no greenhouse gas emissions, no acid rain, no stratospheric ozone depletion and no radioactive waste. It would eliminate dependence on imported fossil fuels from unstable regions of the world, greatly reducing global security risks.
But how do we get from here to there? How do we transition from a transportation system based almost entirely on fossil fuels to one based on renewable hydrogen?

The two main obstacles to this historic transition are the high costs of renewable hydrogen and the current exorbitant cost and unproven reliability of fuel cell vehicles.

The Transition Strategy

Any viable transition strategy must include both an affordable hydrogen fuel pathway and an affordable hydrogen vehicle pathway.

**An Affordable Hydrogen Fuel Transition Pathway**

To provide an affordable hydrogen fuel transition, we propose these incremental steps:

1. Produce hydrogen on-site at the local fueling station initially by reforming natural gas, eliminating the complexity and cost of transporting hydrogen from large central production facilities. In effect we use the existing natural gas pipeline system as the backbone of a distributed hydrogen infrastructure system, eliminating the “chicken and egg” dilemma of not having enough hydrogen cars to support a national hydrogen pipeline system. Producing hydrogen from natural gas will immediately cut greenhouse gas emissions by 45 to 50% compared to today’s gasoline cars.

2. Gradually add hydrogen made from renewable fuels when and where they become affordable, beginning with hydrogen made from ethanol at the local fueling station. In effect ethanol becomes the low-cost transportation vector for delivering hydrogen, building on the existing ethanol distribution system used as a gasoline additive.

**An Affordable Hydrogen Vehicle Transition Pathway**

We propose two steps to introduce hydrogen-powered vehicles:

1. Introduce hydrogen-powered internal combustion engine (ICE) hybrid electric vehicles (HEVs) as surrogates for fuel cell vehicles (FCVs). This option provides an affordable pathway for hydrogen-powered cars before FCVs are proven reliable and economic.

2. Gradually add FCVs as they become affordable and durable.

We explore the economic, environmental and national security impacts of these steps below.

**Hydrogen Delivered Cost**

The least costly option for delivering hydrogen to initial hydrogen-powered vehicles is to produce hydrogen from natural gas at the fueling station, as shown by the first bar in Figure 1 [1,2]. All costs include capital recovery for hydrogen production, compression to 480 bar, storage and dispensing to fill 345-bar car tanks, plus the cost of utilities and delivery in the case of trucked in hydrogen. The hydrogen costs are shown in Euros per litre of gasoline on a range-equivalent basis. For example, hydrogen from the current H2Gen HGM-2000 hydrogen generator module with

* FCV has 2.4 times higher fuel economy than a comparable ICEV; HGM => Hydrogen Generator Module; CR => Capital Recovery

![Figure 1. Cost of delivered hydrogen in €/litre of petrol on a range-equivalent basis compared to a conventional auto](image-url)
Compression and storage would cost approximately €0.53/litre of gasoline on a range-equivalence basis (left bar in Figure 1, or US$2.49/gallon), meaning that a FCV driver would pay the same cost for hydrogen as a conventional car owner would pay for gasoline at €0.53/litre to travel the same distance. The HGM converts natural gas to hydrogen by steam reformation, including a built-in pressure swing adsorption (PSA) gas cleanup system. The cost of hydrogen from this on-site hydrogen production appliance is less than the cost of trucking in either liquid hydrogen or compressed hydrogen in tube trailers. Although hydrogen can be produced for less cost at central facilities than at smaller on-site appliances, the cost of liquefaction or compression and trucking erases this production advantage.

The all-in hydrogen costs in Figure 1 are for the existing on-site HGM-2000 system that could supply approximately 20 fuel cell vehicles per day. However, hydrogen costs will be reduced further in the future with the development of the HGM-10,000 that will produce 264 normal cubic meters of hydrogen per hour (or 10,000 standard cubic feet of hydrogen per hour), enough to fuel 100 cars/day. As shown in Table 1, we estimate compressed hydrogen costs at the fueling station are already competitive with the current average US (fully taxed) gasoline price of €0.59/litre to €0.64/litre, and are much less than costs in Europe and Japan. Within three years we project hydrogen costs at the pump of less than €0.31/litre, or less than the current cost of wholesale gasoline. The cost calculations in Figure 1 and Table 1 are based on economic parameters (annual capital recovery of 16%/year, FCV fuel economy 2.4 times ICEV fuel economy, etc.) used by the National Research Council in their 2004 report on hydrogen [3].

Although on-site hydrogen is least costly with a mature, high capacity system, we anticipate that some hydrogen will still be delivered by truck to provide backup and “peak shaving” capability for the HGM system. Thus on-site and trucked hydrogen will most likely exist together.

**Greenhouse Gas Emissions**

The full well-to-wheels greenhouse gas (GHG) emissions from a fuel cell vehicle are compared with those from a conventional 5-passenger car in Figure 2. The five bars on the right side are all for FCVs, showing dramatically that the source of hydrogen is dominant in determining GHG emissions. For example, electrolyzing water in the US to produce hydrogen for FCVs substantially increases GHGs compared to burning gasoline in a conventional car, since more than half of US electricity comes from burning coal. Producing hydrogen on-site from natural gas will, however, reduce GHG emissions by 45% to 50% compared to driving current cars. These GHG calculations are based on the GREET model developed by Michael Wang at the Argonne National Laboratory [4].

**Table 1. Estimated cost of compressed hydrogen from distributed steam methane reformer systems**

<table>
<thead>
<tr>
<th>Production Cost (€/kg)</th>
<th>Compression &amp; Storage Cost (€/kg)</th>
<th>Total Cost (€/litre)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Today (20 cars/day)</td>
<td>2.96</td>
<td>1.82</td>
</tr>
<tr>
<td>3 Years (100 cars/day)</td>
<td>2.08</td>
<td>0.70</td>
</tr>
<tr>
<td>6 Years (100 cars/day)</td>
<td>1.87</td>
<td>0.55</td>
</tr>
<tr>
<td>~10 Years (250 cars/day)</td>
<td>1.68</td>
<td>0.49</td>
</tr>
</tbody>
</table>

Assumptions: Annual Capital Recovery factor = 16%; Capacity Factor = 90%; Natural Gas = EUR7/MBTU; Electricity = 8 cents/kWh; FCV fuel economy = 2.4 X ICEV; $1 = 0.808 €

**Figure 2. Estimated greenhouse gas emissions for fuel cell vehicles compared with a gasoline car, demonstrating that the source of the hydrogen determines GHG emissions.**
The two bars on the right of Figure 2 show substantially reduced GHG emissions with renewable hydrogen options, starting with hydrogen made from ethanol at the fueling station. These options will still produce some GHG today, due to the large quantities of fossil fuels used for farming operations including production of fertilizers, herbicides, pesticides, and tilling the land and harvesting the corn, combined with fossil fuels used to run the ethanol plants and the diesel fuel used to transport the ethanol to the fueling station. In the future, even these small GHG contributions will be reduced as more of the agriculture and ethanol industries switch to renewable fuels.

Fuel Costs and Greenhouse Gas Emissions

The previous sections have treated fuel costs and GHG emission separately. The following two figures plot GHG emissions versus fuel cost, illustrating the best options to achieve both low fuel cost and low GHGs. Figure 3 shows the full range of options including the existing cars (ICEVs), gasoline-powered HEVs, plug-in HEVs, as well as a hydrogen-powered cars (both ICE HEVs and FCVs) with six different sources of hydrogen (grid electrolysis, PV electrolysis, wind electrolysis, on-site natural gas reforming, on-site corn ethanol reforming and on-site cellulosic ethanol reforming.)

![Figure 3](https://example.com/figure3.png)

**Figure 3.** Greenhouse gas emissions plotted against fuel costs per km, comparing gasoline cars with hydrogen cars (both ICE HEVs and FCVs) and six different hydrogen fuel sources

The best options (lower left hand corner of Figure 3) are plotted in Figure 4 with an expanded scale, showing that on-site reforming of cellulosic ethanol produces hydrogen at a cost that is up to three times lower than fuel costs for conventional autos, and half the fuel cost of gasoline-powered HEVs but with an 80% reduction in GHGs.
Some analysts have suggested that we should exclusively embrace gasoline-powered hybrid electric vehicles (HEVs) like the Honda Insight or the Toyota Prius. While we also advocate the adoption of gasoline HEVs in the near term, we are concerned that gasoline HEVs actually offer only a short-term reprieve from society’s steady increase in GHG emissions and oil consumption. To illustrate this effect, we have written a 100-year computer simulation of GHGs and oil consumption for the US, comparing five options:

- Business-as-usual with conventional internal combustion engine vehicles (ICEVs)
- A gradual transition to gasoline HEVs with 50% new car sales by 2015
- A gradual transition to plug-in gasoline HEVs with 50% new car sales by 2015
- A gradual transition to hydrogen ICE HEVs with 50% new car sales by 2023
- A gradual transition to hydrogen FCVs with 50% new car sales by 2030

The upper curve of Figure 5 shows that GHGs will increase steadily with the business-as-usual approach as people travel more each year. The second curve (labeled “Gasoline ICE HEV”) shows that HEVs offer only a momentary reprieve from increased GHG emissions. Once vehicle miles traveled cancels out the increased fuel economy of HEVs, GHGs rise inexorably thereafter.

We also modeled plug-in battery hybrids where the owner plugs a gasoline HEV

![Figure 4. Scale change showing the best fuel/vehicle options](image-url)
into the power grid when the car is parked, recharging the batteries. In the US, deriving energy from the grid for a plug-in HEV coincidently produces almost the same greenhouse gas emissions as burning gasoline in that same HEV. Hence the curves for gasoline-powered HEVs and plug-in HEVs are superimposed in Figure 5.

The two lower curves of Figure 5 show that only hydrogen-powered cars can make a substantial long-term reduction in GHGs. In this simulation, we have assumed that all hydrogen is made initially from natural gas, but that we transition gradually over the century to renewable hydrogen, such that by 2050 half of all hydrogen comes from some combination of renewable sources.

Figure 6 shows the oil consumption patterns for the same simulation, with the similar results: gasoline-HEVs are but a momentary lull in the steady increase in oil consumption, and only renewable hydrogen offers the potential for dramatically reducing our dependence on imported oil. In this case it does not matter whether the hydrogen car is an ICE HEV or a FCV. For every hydrogen HEV on the road, one gasoline car is eliminated, cutting gasoline consumption.

Plug-in HEVs do cut oil consumption. We have assumed here that on the average plug-in hybrids derive 40% of all energy from the grid, and 60% from gasoline. But even in this case rising vehicle miles traveled toward the end of the century would again create a steadily rising dependence on imported oil. Furthermore, there is considerable doubt in the auto business that sufficiently robust and low-cost batteries can be developed to satisfy both the deep-discharge energy characteristics demanded by a plug-in hybrid and the micro-cycling power requirements of the HEV itself for hill climbing and acceleration. This may explain why most car companies are concentrating on the development of fuel cell vehicles instead of plug-in hybrids.

Conclusions

With regard to hydrogen fuel, we conclude that:

- Hydrogen can be made from natural gas at the local fueling station with fully loaded costs (including compression, storage and dispensing) that are competitive with gasoline per mile driven in either a conventional or HEV.
- Hydrogen fueling appliances can be added incrementally to fueling stations when and where needed to match hydrogen vehicle demand, thereby avoiding the “chicken and egg” dilemma of a national hydrogen pipeline system.
- Hydrogen made from ethanol at the fueling station is the least costly renewable hydrogen option, and will likely remain so for many decades.
- Hydrogen made from cellulosic ethanol is cost competitive with gasoline per mile driven, but with at least 80% lower greenhouse gas emissions.

With regard to motor vehicles, we conclude that:

- Hydrogen-powered internal combustion engine hybrid electric vehicles (ICE HEVs) can be introduced much earlier than FCVs due to much lower cost and greater reliability.
• Gasoline-powered HEVs are a dead-end street with respect to greenhouse gas emissions and oil dependence since they will not provide for any long-term reductions in either GHGs or in oil imports.

• Plug-in HEVs could temper the steady rise in oil dependence provided suitable batteries can be developed for both deep discharge and micro-cycling, but they will not have any significant impact on GHG emissions compared to gasoline HEVs.

• Either hydrogen ICE HEVs or hydrogen FCVs offer the potential for dramatic reductions in both GHGs and oil imports, approaching zero in both cases, provided that hydrogen is eventually made from some combination of renewable sources in the middle to end of this century.

References


Acknowledgements

The authors acknowledge the many contributions of all H2Gen employees in making on-site reforming of natural gas an economic reality. We especially thank Dr. Frank Lomax, VP of Technology, the inventor of the HGM system and founding member of H2Gen who has been instrumental in the development and commercial implementation of this unique hydrogen fueling appliance technology. We also express our gratitude to our major investors (@Ventures, Air Products & Chemicals, Areté, Calvert Social Funds, Commons Capital, Hydrogenica, Itochu, Nth Power, and the Southern California Gas Company. Finally, we acknowledge the support of Steve Chalk and his team at the U.S. Department of Energy that funded the early hydrogen infrastructure work at the Ford Motor Company and Directed Technologies, Inc. that led to the formation of H2Gen, and also acknowledge the support of Arlene Anderson and Pete Devlin in Steve Chalk’s office through the recent DOE contract DE-FG36-05GO15026 to H2Gen to further reduce the costs of on-site hydrogen production and to demonstrate low-cost hydrogen made on-site from ethanol.