August, 2008

The NHA Hydrogen Transportation Story
Executive Summary: DRAFT[1]

[1] This Consensus Document does not necessarily represent the organizational views or individual commitments of all members of the National Hydrogen Association.

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Executive Summary

Background

The economic progress of the last century has been built largely on petroleum. The growing global demand for and finite supply of oil and the mounting effects it is having on the environment, however, amplify the need to have multiple sources of energy that are non-polluting, inexhaustible, and readily obtained, preferably from domestic sources. Hydrogen is the ultimate zero emission fuel that can link these clean, renewable energy sources to end uses such as powering vehicles, factories, businesses and homes.

Although the most plentiful element in the universe, hydrogen does not exist independently; it must be separated from other sources such as carbon-based fuels, biomass, or water. The process of separating hydrogen from carbon-based fuels is called reforming. The process of separating hydrogen from water using electricity is called electrolysis. The captured hydrogen can be fed into a combustion chamber to power internal combustion engines or channeled through a fuel cell that directly converts the energy from hydrogen into electricity. In both of these processes, the hydrogen reunites with oxygen from the air and forms water. If the hydrogen is produced from clean sources (such as from renewable or nuclear energy), the complete process can be virtually pollution free.

Industry has already demonstrated a solid track record of safely and economically producing and working with hydrogen. A large hydrogen market and infrastructure exists today, primarily supporting the oil refining and industrial chemical industries, and new hydrogen markets are emerging, including transit fleets, decentralized power, emergency power and industrial applications. The next important step is to transition the transportation sector to hydrogen.

Why Hydrogen?

Hydrogen used in a fuel cell electric vehicle is the only light-duty transportation option that could *simultaneously*:

- Cut greenhouse gas (GHG) pollution by 80% below 1990 levels late in this century (the level recommended by the U.S. Climate Action Partnership);
- Reach petroleum energy quasi-independence[2] by mid-century;
- Eliminate nearly all controllable urban air pollution by the end of the century.

Consumers need not sacrifice their lifestyle to benefit from using hydrogen. Quiet, fuel-efficient fuel cell vehicles can be made to look, feel and refuel like today's automobiles, yet significant new opportunities to improve the overall driving experience are possible. The fueling infrastructure supporting large volume deployment of fuel cell electric vehicles can be commercially viable in the range of $2-3 dollars per gallon of gasoline equivalent[3].

Great progress has been made in the last decade in hydrogen production, storage, and delivery, and fuel cell vehicle and distributive energy technologies. Though many challenges face the full implementation of the energy-independent and virtually pollution-free economy enabled by hydrogen, solutions to those challenges are within reach and, in many respects, are prone to fewer side effects than the alternatives. They can be attained with less investment than is required for maintaining the existing oil and gas infrastructure, while reaping staggering societal cost savings[4], which result from cleaner air and less dependence on foreign energy resources.

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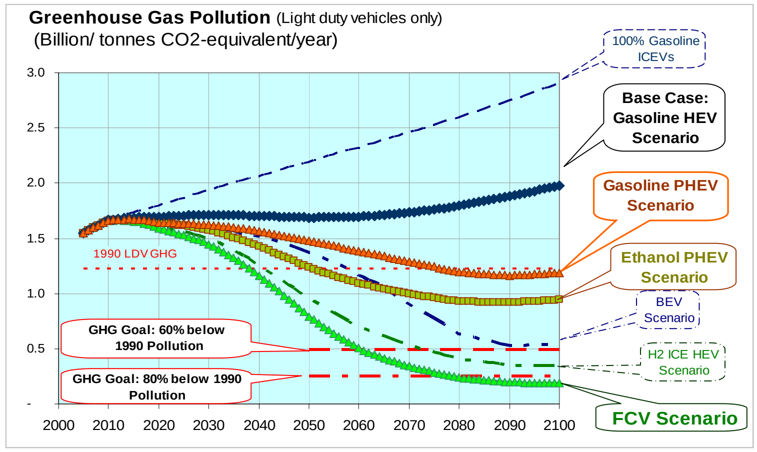
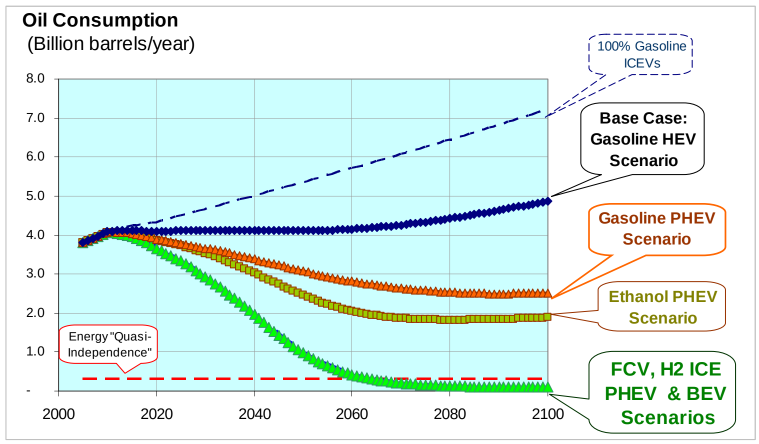
[2] By energy "quasi-independence" we mean that the use of petroleum products in the transportation sector would be reduced to such a level that all our remaining transportation and non-transportation needs could be fulfilled by domestic oil production in a crisis, vastly improving our energy security.

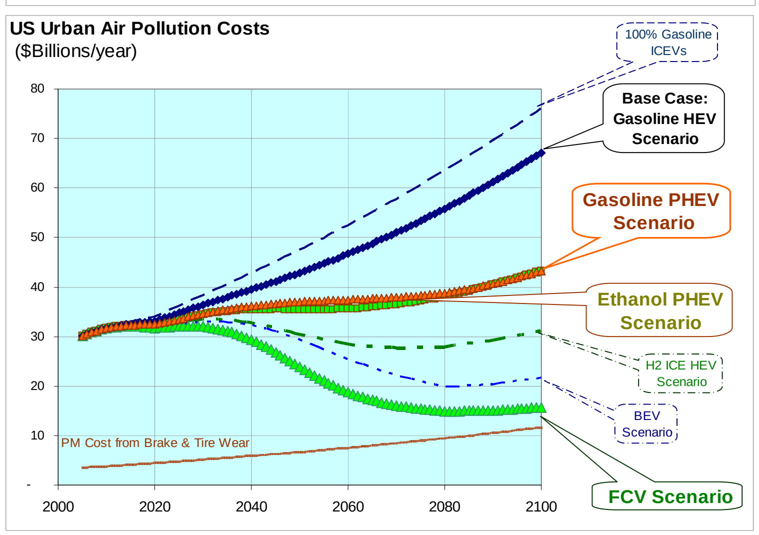
[3] Hydrogen would cost $4-6 per kilogram. Since a fuel cell is at least twice as efficient as an internal combustion engine, and since one kg of hydrogen has approximately the same energy content as one gallon of gasoline, then the cost per mile in a FCV would be similar to that of gasoline at $2-3 per gallon used in a conventional gasoline car.

[4] Greenhouse gas, urban air pollution and oil consumption calculated using the Argonne National Lab GREET 1.8a model

Even broader economic benefits will accrue as a result of adopting hydrogen, positively affecting our ability to compete in the global economy and our ability to draw on a variety of different sources of energy. The benefits of energy source diversity cannot be overstated. Each of the energy sources for hydrogen production is, to a greater or lesser extent, produced domestically. This has the effect of mitigating the impact of energy price fluctuations or macroeconomic risks that flow from our heavy dependence on imported oil and leave us less dependent on energy from regions that are beset with political risk. An even greater benefit, however, flows from hydrogen's effect on the competitive forces that contain costs. Hydrogen's ability to draw on multiple energy sources encourages greater competition within the energy industry, rather than steering investment toward a single source and recreating the heavy dependency we now have on petroleum. This should lower the cost of energy, improve the cost competitiveness, and increase the rate of return on investing and producing goods and services in the United States.







What about the other options?

The other mainstream fuel/drive train options (battery electric vehicles and internal combustion hybrid electric vehicles fueled by gasoline, diesel, ethanol, and hydrogen) will play an important role in making the transition away from petroleum-based fuels. Development of hybrid vehicles synergistically advances development of the electric drive train and battery storage needed in fuel cell electric vehicles, for example.

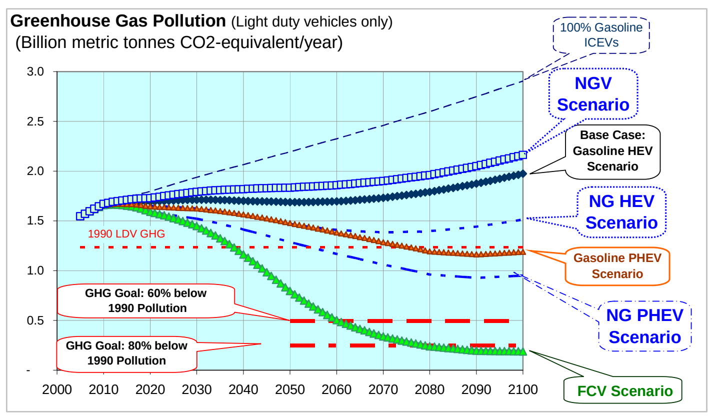
- **Battery-electric vehicles (BEV)**, if accepted by consumers[5], could be second best to fuel cell electric vehicles, cutting GHGs by 60% below 1990 levels, achieving energy quasi-independence and nearly the same urban air pollution reduction as hydrogen. Battery and hydrogen fuel cell technologies are highly complementary, and in any long-term scenario where clean energy, energy security and economic vitality are the end-game criteria, both batteries and hydrogen will play a major role.
- **Gasoline hybrids (HEV)** could initially cut the rate of growth of GHGs, oil consumption and urban air pollution, but all three would continue to rise with more miles traveled each year.
- **Gasoline plug-in hybrids (PHEVs)** would make further cuts in pollution and oil use, but GHG pollution would at best return to just below1990 levels.

[5] All-electric BEVs may not achieve driver acceptance due to limited range (due to low battery specific energy in kWh/kg, and hence, large size and weight) and long battery recharging times.

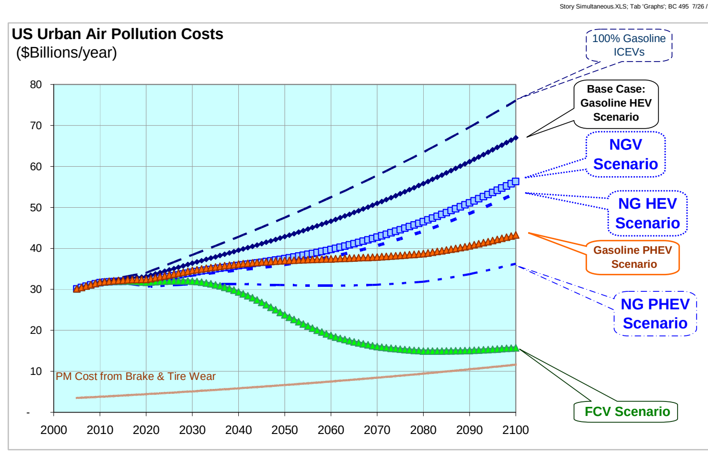
- Oil consumption would remain at 2.5 billion barrels/year.
- Urban air pollution levels would continue and even rise.

- **Ethanol plug-in hybrids (EPHEV)** could:
  - Cut GHG pollution to 25% below 1990 levels.
  - Cut oil consumption to 2 billion barrels/year (still four times the energy quasi-independence level).
  - Make no improvement in urban air pollution over gasoline PHEVs, according to the Argonne GREET model.
- **Hydrogen internal combustion engine hybrid electric vehicles (H2 ICE HEVs).** Burning hydrogen in conventional ICEs would:
  - Provide almost the same GHG reductions as fuel cell vehicles, approaching 70% below 1990 levels by the end of the century.
  - Cut oil consumption by the same amount as FCVs.
  - Decrease urban air pollution slightly below current levels, although urban air pollution would begin to rise at the end of the century if all hydrogen were burned in ICEs.

There are two other alternative fuel options under consideration for reducing the impact of gasoline: diesel fuel and compressed natural gas. Neither option would be sustainable in the long term, since they both rely on finite fossil fuels. But they could be used to reduce the environmental impact and petroleum dependence of burning gasoline to some degree.



- **Diesel ICEVs.** Replacing gasoline ICEVs with diesel ICEVs will have minimal impact on the environment or energy security. Diesel compression-ignition engines have slightly higher efficiency than gasoline spark-ignited engines, so they will have slightly less GHGs emissions and consume slightly less petroleum than gasoline ICEVs[6].



- **Natural gas vehicles (NGVs).** Natural gas vehicles would have a greater impact, since natural gas burns cleaner than diesel or gasoline, and using natural gas would at least diversify our sources of energy for transportation. With respect to GHGs:
  - (non-hybrid) NGVs would reduce GHGs compared to gasoline ICEVs, but not as much as gasoline HEVs.
  - NG HEVs would keep GHGs close to today's levels, but still higher than 1990 levels.
  - NG plug-in hybrids (PHEVs) would reduce GHGs to approximately 20% below 1990 levels, about the same level as the ethanol PHEVs. Thus natural gas under the most optimistic assumptions could not achieve the major GHG reductions deemed necessary to avert major climate change events.

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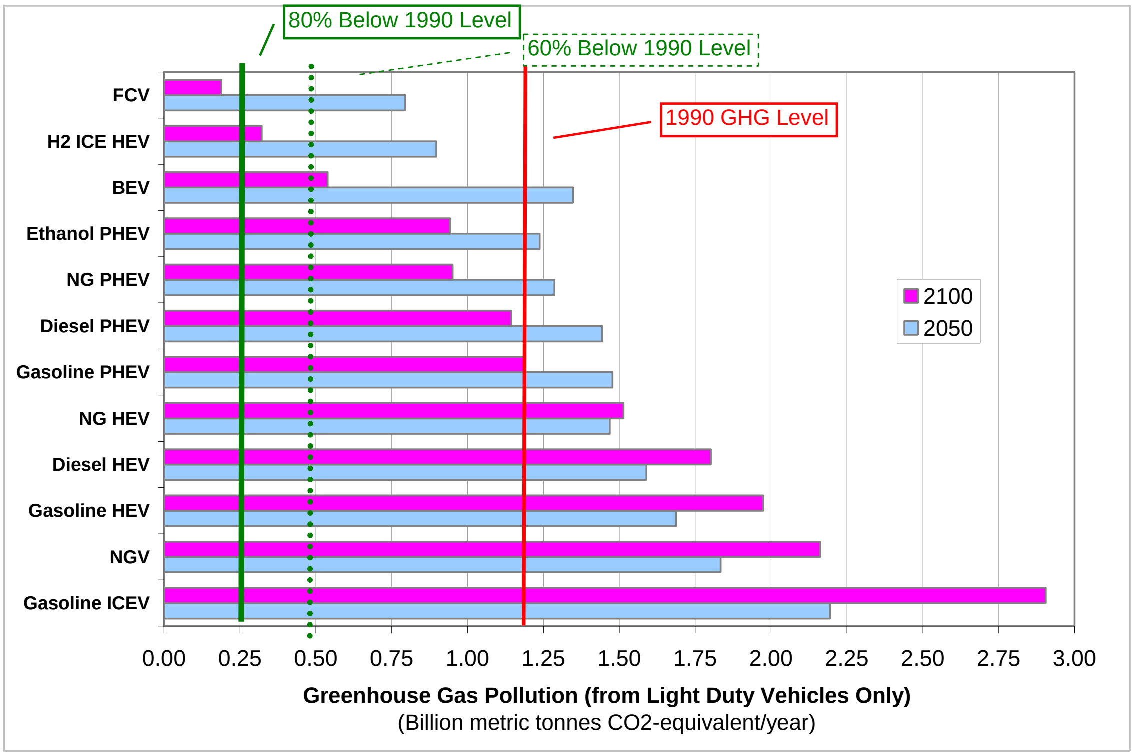
[6] The graphs lines for GHGs and oil consumption for diesel ICEVs, HEVs and PHEVs lie just below the equivalent lines for gasoline ICEVs, gasoline HEVs, gasoline PHEVs.

- In terms of urban air pollution, natural gas used in either a conventional ICEV or an HEV would produce substantially rising pollution over the century. A natural gas PHEV would at best produce the same urban air pollution as today's cars, and even the NG PHEV air pollution would begin to rise by the last quarter of the century.

The following chart captures GHG emission snapshots for two years: 2050 and 2100 for most of the vehicle/fuel scenarios considered in this simulation. This chart again illustrates that the hydrogen-powered fuel cell vehicle is the only option that could achieve an 80% reduction below 1990 GHG levels, although the hydrogen ICE HEV comes close. This chart also demonstrates the small differences between gasoline, diesel and natural gas fuels for HEVs and for PHEVs. Diesel fuel reduces GHGs slightly compared to gasoline, while natural gas has a larger impact. Note also that for non-plug-in HEVs, GHGs are larger in 2100 than in 2050.



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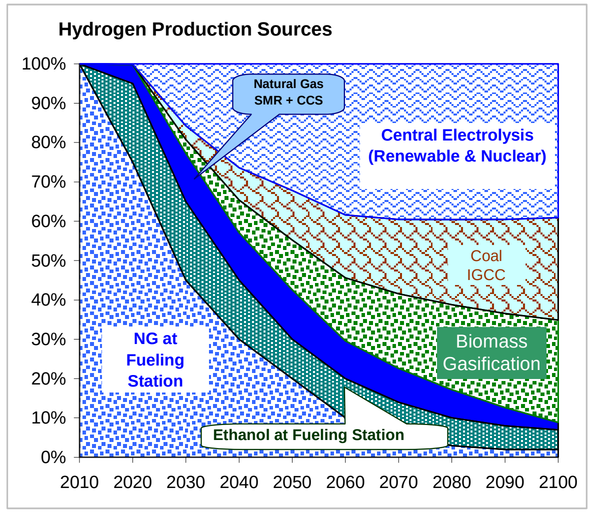
Key Simulation Assumptions

- These computer simulations optimistically assume that all technical/economic issues are favorably resolved:
- For fuel cell vehicles, vehicle costs become competitive; hydrogen is affordable, available and transitions over time to low-carbon sources.
- For plug-in hybrids, affordable deep-discharge lithium ion batteries achieve their specific energy goal of 150 watts/kg, the electrical grid is converted to low-carbon sources, and up to 75% of vehicles have access to night-time charging outlets.
- For battery electric vehicles, affordable batteries are developed that can provide 250- to 300-mile range with fast recharge times of less than 20 minutes to allow cross-country travel.



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- Key Fuel Source Assumptions:
  - Hydrogen is made from natural gas initially, transitioning to hydrogen from biomass, from coal and natural gas with carbon capture and storage (CCS) and eventually from electrolysis of water using renewable and nuclear electricity.
  - Electricity to charge plug-in hybrids and BEVs is assumed to be made from the west coast grid mix that has less coal generation and more hydroelectricity than the rest of the nation, transitioning to more renewable electricity, coal with CCS, and more nuclear power. Plug-in hybrids have all-electric ranges between 12 to 52 miles, and derive from 18% to 65% of their energy from the electrical grid.
  - Ethanol for plug-in hybrids is made initially from corn, transitioning to hemi-cellulose and cellulose feedstocks over the century, with production of cellulosic ethanol or equivalent rising to 120 billion gallons per year by mid-century.
- Key Market Penetration Assumptions:
  - Alternative vehicles enter the market according to modified logistics curves, with HEVs reaching the potential for 50% annual sales by 2024, PHEVs by 2031 and FCVs by 2035.
  - Multiple types of alternative vehicles are assumed to be sold each year.