Chapter 7
Hydrogen as a Vehicle Fuel[1]

Using hydrogen as a vehicle fuel offers another option for reducing oil use while addressing problems of urban air pollution and, possibly, global warming as well. A hydrogen-fueled vehicle should emit virtually no hydrocarbons, particulate, carbon dioxide, or carbon monoxide;[2] the only significant air pollutant emitted would be NO_x. And because hydrogen can be produced through electrolysis of water using nonfossil electricity-nuclear, biomass, hydroelectric, or solar-a fleet powered by hydrogen conceivably could generate no net carbon dioxide and only minor quantities of other greenhouse gases.

FUEL SOURCE

Hydrogen is available from a number of sources. It can be produced from any hydrocarbons by several processes. For example, combining natural gas and steam (steam reforming) will produce hydrogen and carbon monoxide, or natural gas can be heated in the presence of a catalyst to be "cracked" into carbon and hydrogen. Coal (or biomass) can be gasified by combining it with steam under high pressure and temperature, forming carbon dioxide and hydrogen.[3] Or hydrogen can be obtained from water by applying high temperatures, with or without other chemicals, to decompose the water (thermal and thermochemical decomposition); by adding an electrolyte and applying a current to the water (conventional electrolysis); by electrolyzing steam rather than water (high-temperature steam electrolysis); or by using light with a chlorophyl-type chemical to split out the hydrogen (photolysis). At the moment, steam reforming of natural gas is the least expensive production method. The near-term production system with the largest resource base-coal gasification—will create substantial negative impacts from mining, from CO_2 emissions, and, with some gasifiers, from waste disposal problems associated with carcinogenic tars and other residues from the gasification process. The latter problem can be reduced or avoided by using higher temperature gasifiers.

VEHICLES AND FUEL STORAGE

Although hydrogen can be carried onboard a vehicle in a number of different ways, the two methods that have received the most research attention are as a liquid in cryogenic (ultra cold) storage or as a gas bound with certain metals in a hydride, and released gradually by heating the hydride.

Both systems still have substantial limitations compared to gasoline vehicles. Refueling should be similar to refueling natural gas-powered vehicles: refueling time with a hydride system should be longer than required for gasoline vehicles and may represent a market barrier; liquid hydrogen refueling may be less of a problem. Existing hydride storage systems must be very heavy and large, because they can store only a few percent hydrogen by weight[4]; hydrogen vehicles using such a storage system will have limited range between refueling and reduced storage space, performance, and efficiency compared to cryogenic systems. Ongoing research is aimed at developing a hydride storage system that can store a higher percentage of hydrogen by weight than the 3.5 percent or so that is the current practical maximum for such systems. A developer has recently made claims of a storage rate of about 7 percent using nickel-hydride in an amorphous form.[5] This high a storage rate would make a hydride-based system much more competitive. OTA is not aware of independent confirmation of the claim, however.

Cryogenic systems will not be much heavier than gasoline storage systems, so performance will not suffer. However, cryogenic storage also has impor-

[1] This section is based primarily on M.A. DeLuchi, "Hydrogen Vehicles: An Evaluation of Fuel Storage, Performance, Safety, Environmental Impacts, and Cost,'' *Int. J. Hydrogen Energy*, vol. 14, No. 2, Pergamon Press, 1989. Information from other references is cited in the footnotes following this one.

[2] The only source for these emissions will be the combustion of small quantities of engine oil, particularly in older vehicles.

[3] Biomass may hold an advantage here because some biomass gasifiers do not require oxygen.

[4] For most materials, the weight of hydrogen stored is only 0.5 to 2.0 percent of the total weight of the storage tank, although a magnesium system, modified to account for the high temperature needed to maintain fuel flow from a pure magnesium system, will store as much as 3.6 percent by weight.

[5] "Ovonic licenses Hydride Battery to Varta,'' *The Hydrogen Letter,* March 1989, vol. IV, No. 3.

tant problems. Its bulkiness will reduce vehicle space; even accounting for improved vehicular efficiency with hydrogen, such a storage system must be five or six times bulkier than a gasoline tank sized for the same range. Further, the fuel tanks' generally spherical shape is difficult to integrate into a vehicle design. Also, cryogenically stored hydrogen will begin to boil off if the vehicle is not used for a few days, as heat seeps through the insulation. This is a problem from both a safety and economic (fuel loss) standpoint, though the former is probably more important; if the vehicle is stored in an enclosed area, the leaked hydrogen could form an explosive hazard. Solutions to this problem could be either to burn off the gas or vent it.

EMISSIONS AND PERFORMANCE ATTRIBUTES

In addition to the differences in storage system volume and weight, hydrogen-fueled vehicles will differ from gasoline vehicles because of hydrogen's unique properties as a fuel. As with all other fuels, engine efficiency, performance, and emissions from a hydrogen-fueled engine are interdependent, and maximizing one attribute may increase or decrease the others. Nevertheless, the thermal efficiency of a hydrogen engine should beat least 15 percent higher than its gasoline counterpart, based on available tests.[6] Power may be higher or lower, with a major factor being the form in which the hydrogen is injected into the cylinders.[7] And as with other fuels, operating very lean will increase efficiency and reduce uncontrolled NO_x[8] at the expense of power and driveability. In general, it should be possible to keep NO_x emissions at levels at or below those of a catalyst-equipped gasoline vehicle, using only exhaust gas recirculation without exhaust treatment, while maintaining adequate power and high efficiency. And, aside from minor emissions associated with burning small quantities of engine oil, the hydrogen vehicles should emit no other air pollutants. Consequently, with appropriate selection of the remainder of the system, a hydrogen-based fleet could have a significant positive effect on urban air pollution.

SAFETY

In addition to the potential safety problem associated with boiling off of cryogenically stored hydrogen, such a hydrogen system has a few other safety concerns. In particular, hydrogen is easily ignited and, once ignited, will burn rapidly yet invisibly and odorlessly—which could cause a detection problem. Also, in an enclosed space, it is more likely to explode than an equal concentration of methane or gasoline vapors if contacted by a flame.[9]

Despite these potential problems, hydrogen is not considered a particularly dangerous fuel. Any problems associated with its lack of odor or visible flame should be solvable with additives. In some situations, its properties should *add* to safety, for example, it will disperse or evaporate extremely quickly in the event of a leak, in comparison to gasoline, which evaporates more slowly and is likely to remain a hazard until physically removed. Also, it is nontoxic and noncarcinogenic. And in hydride form, major leaks will not occur, and thus a hydride fuel system should be quite safe.

DEVELOPMENT REQUIREMENTS

The components necessary to create a hydrogen-fueled fleet-hydrogen storage and delivery systems, large-scale hydrogen production systems, and hydrogen-fueled engines-are all at an early stage of research or development. Coal gasification systems may be the closest to becoming fully commercially; the Cool Water integrated coal gasification combined cycle plant based on the Texaco gasifier has performed extremely well from both an operational and an environmental viewpoint, and the next

[6] Tested efficiencies range up to 50 percent higher than gasoline, though some analysts are extremely skeptical of the applicability of the higher values to a practical commercial vehicle. Note that with a hydride system, *vehicle* efficiency will suffer because of the added weight of the fuel storage system.

[7] Because hydrogen in gaseous form has a low energy density, engine power using hydrogen in this form will be lower than its gasoline counterpart. To recapture some of this power loss, or possibly to attain an increase, the fuel can be injected either as liquid hydrogen (if cryogenic storage is used) or at very high pressures. Liquid hydrogen injection systems are technically demanding, and high pressure systems have not yet been tested.

[8] But preclude the use of a reduction catalyst for additional NO_X control, because these catalysts cannot operate in a lean (oxygen rich) environment.

[9] Hydrogen has extremely wide flammability limits, 4 to 74 percent. *Handbook of Chemistry and Physics, Forty Fourth Edition* (Cleveland, OH: Chemical Rubber Publishing Co., 1962), compared to, for example, methane with flamiability limits of 5 to 15 percent. What this means is that virtually any concentration of hydrogen in air, except one below 4 percent, can explode.

[10] The L@ gasifier is fully commercial—and some others are arguably commercial—as producers of synthesis gas, a combination of hydrogen and carbon monoxide.

generation technology is expected to achieve substantial improvements in cost and efficiency. The Japanese and West Germans have strong vehicle development efforts, but these have produced only a small number of prototype vehicles, and major uncertainties remain about the configuration and performance of an optimum hydrogen engine. Current hydride storage systems impose a substantial range and performance penalty because of their high weight and volume, and a breakthrough in storage technology may be needed to produce a marketable vehicle. Work needs to be done on pipeline transport, because pure hydrogen will damage certain steels, and inhibiting agents to be added to the hydrogen must be found--or a separate pipeline infrastructure must be built. And if the greenhouse gas problem associated with coal as a hydrogen source is to be avoided, substantial advances in large-scale electrolysis systems, hopefully based on solar energy, must be accomplished.

COST COMPETITIVENESS

With these uncertainties, the costs of a hydrogen-based system are speculative. One interesting cost analysis that attempts to trace full lifecycle costs for the entire hydrogen system calculates a range of gasoline ''break even' prices-the price of gasoline for which a hydrogen system would be fully competitive, assuming the gasoline and hydrogen vehicles were roughly equivalent in size.[11] This analysis estimates the break-even gasoline price for a system based on coal gasification to range from about $1.50 to $5.00/gallon in 1985 dollars. The gasoline price computed for a system based on solar photovoltaic-generated electricity and electrolysis ranges from about $3.50 to $12-$ 14/gallon, with even the higher value assuming electricity costs substantially below that obtainable with current solar technology.

Recent improvements in photovoltaic (PV) technology have convinced some analysts that hydrogen can be generated at costs considerably below those estimated above.[12] Hydrogen delivered to vehicles at gasoline-equivalent costs below $2.00/gallon may be possible if substantial improvements can be made in PV module cost and efficiency, e.g., module production cost for amorphous silicon solar cells reduced from the current $1.60/peak watt to $0.20 to $0.40/peak watt, and module efficiency improved from 5 percent to 12 to 18 percent.[13]

Given the high level of uncertainty, these cost figures should be viewed cautiously. Of the alternative fuels considered here, hydrogen appears to be the furthest from commercial availability. The amount of development work remaining for all phases of the fuel cycle essentially guarantees that a commercial system will look very different from current conceptual systems—with, presumably, quite different actual costs than estimated here. Further, the analysis compares vehicles that are not identical, so that the direct cost comparisons, even if they were accurate, could be misleading from a market attractiveness standpoint. For a vehicle with cryogenic storage, performance and range could be comparable to that of a gasoline vehicle of equal *overall size*, but the hydrogen vehicle would have substantially less storage space than the gasoline vehicle. For a vehicle based on hydride storage, performance and range would be substantially inferior to the gasoline vehicle unless a substantial breakthrough were made in hydrogen storage capacity and power was increased by using a larger engine or untested high pressure gas injection.

Because hydrogen vehicles emit no $C0_2$, they may be viewed as especially attractive component of a strategy to reduce global warming trends. Their value as such a component depends on fuel production, however. Although the lowest cost coal-based system would be competitive with gasoline at

[11]DeLuchi, op. cit., footnote 1.

[12]J.M. Ogden and R.H. Williams, ***The Prospects for the Production and Utilization of Hydrogen Produced Via Electrolysis Using Amorphous Silicon Solar Cells,*** draft report to the Office of Technology Assessment, December 1988; and same authors, ***Solar Hydrogen: Moving Beyond Fossil Fuels,*** World Resources Institute, October 1989.

[13]Ibid. The cost reduction is obtained by gaining economies of scale by increasing output from 10 to 100 MWp/yr; increasing module efficiency to 12 to 18 percent, increasing the plant depreciation period from 5 to 10 years, reducing materials costs from $27.6 to $13.2/square meter, and reducing balance-of-system costs from $50 to $33/square meter. The authors compute PV electricity, in DC form, generated by these modules at $0.020 to $0.035/kilowatt-hr, and PV hydrogen at a gasoline-equivalent cost of $1.11 to $1.70/gallon. The authors also use utility accounting and assume purchase of PV modules at cost, predicated on the development of large remote electricity generating and hydrogen production sites by a utility-type organization that purchases PV manufacturing facilities rather than individual assemblies. Further, the authors calculate costs of both hydrogen and alternative fuels based on zero income and property taxes, to rid the comparison of PV hydrogen and alternative transportation fuels of a tax system bias against capital-intensive projects. Inclusion of these taxes would raise the gasoline break-even prices somewhat.

$1.50/gallon, a price that is easily imaginable within a few years, the coal-based system—which would produce high levels of CO_2 emissions during hydrogen production—would be extremely damaging to efforts to reduce greenhouse gas emissions unless it was designed only as a precursor to a system based on renewable or nuclear energy, or unless the CO_2 generated in the fuel production could be sequestered rather than released to the atmosphere. PV-based or nuclear-based systems would produced essentially no greenhouse gases, but they are likely be more expensive than coal-based systems, at least compared to the lower end of the coal range, even with the sharp cost reductions discussed for PVs; biomass-based systems might become cost-competitive with coal-based systems, however, if biomass gasifiers were improved.

HYDROGEN OUTLOOK AND TIMING

In Summary, the use of hydrogen as a vehicle fuel has strong appeal from a pollution control standpoint, and could aid in efforts to slow global warming if the hydrogen was produced from non-fossil sources. However, much development work needs to be done before a hydrogen-based system could be practical, and the likely cheapest system—a fossil-based system—would have strong negative implications for global warming and may have other environmental shortcomings. On the other hand, if PV-based electricity generation fulfills the hopes of solar optimists, solar-based hydrogen could eventually be cost-competitive with coal-based hydrogen and with gasoline priced at $2.00/gallon and below.

Aside from costs, hydrogen's major roadblock may be its bulkiness-hydrogen's low energy density implies either very limited range between refueling or very large, heavy fuel tanks. Unless there is a major breakthrough in hydride storage or in vehicle efficiency (which would ease the range problem), hydrogen-fueled vehicles cannot provide a close substitute to gasoline-powered vehicles. Given the need for important scientific development in several areas, hydrogen must be considered a long-term prospect as an alternative transportation fuel.