Getting Along without Gasoline—The Move to Hydrogen Fuel

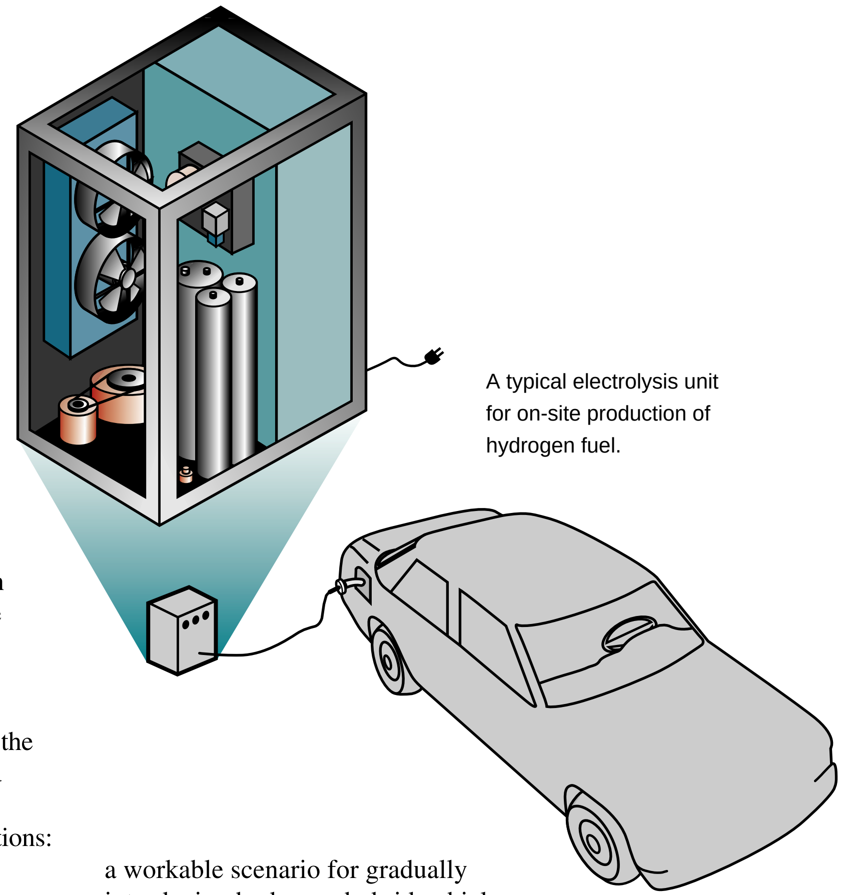
SCIENTISTS and engineers from Lawrence Livermore's Energy Directorate recently found themselves on the horns of a dilemma. They had designed a concept hybrid-electric vehicle—optimized for hydrogen fuel—that meets state and federal guidelines and requirements for alternative "light-duty" vehicles (cars, vans, and small trucks).[1] Its acceleration ability and driving range equal or exceed those of comparable gasoline-powered vehicles, but it does not rely on imported oil and does not have the environmental drawbacks of the gasoline-powered internal combustion engine. The dilemma was that despite the team's conceptual design successes, hydrogen hybrid vehicles will not be driven in significant numbers until there is a reliable infrastructure to supply the hydrogen fuel, but neither will a hydrogen supply infrastructure develop until there is a sufficient market demand.

To resolve this dilemma, a multidisciplinary team from the Laboratory's Energy Directorate undertook a technical and economic feasibility study of the near-term potential of hydrogen transportation fuel.[2] It addressed four basic questions:

- Can a hydrogen vehicle compete with today's cars?
- How can hydrogen fuel be distributed to users?
- What will be the cost of hydrogen as a transportation fuel?
- How does hydrogen compare to other alternative fuels?

Furthermore, the study sought to establish a scenario for the simultaneous emergence of hydrogen-powered light-duty vehicles and a fuel-supply infrastructure to support them.

The results of the team's investigation are extremely promising. Using conservative assumptions, the investigation indicates that hydrogen-powered, hybrid-electric light-duty vehicles are technically and economically feasible solutions to the oil import and environmental problems of gasoline-powered vehicles. In addition, hydrogen is environmentally superior to any alternative fuel. Finally, the study confirms the near-term feasibility of the transition to an infrastructure for manufacturing and supplying hydrogen fuel and suggests



A typical electrolysis unit for on-site production of hydrogen fuel.

a workable scenario for gradually introducing hydrogen hybrid vehicles and the fuel to power them. The key to this feasibility is to make hydrogen at the point of use and to use the existing electric and natural gas networks to distribute the fuel.

The Hydrogen-Fueled Concept Car

The hybrid-electric vehicle being developed at the Laboratory (Figure 1) would burn hydrogen in a small, optimized internal combustion engine to run a generator charging an electrical storage system that in turn would power an electric motor. The engine would run only as needed to charge the storage system and at optimum speed and maximum efficiency. The five-passenger vehicle is designed to accelerate from 0 to 96 km/h (60 mph) in 8 seconds and would require only about 3.75 kg

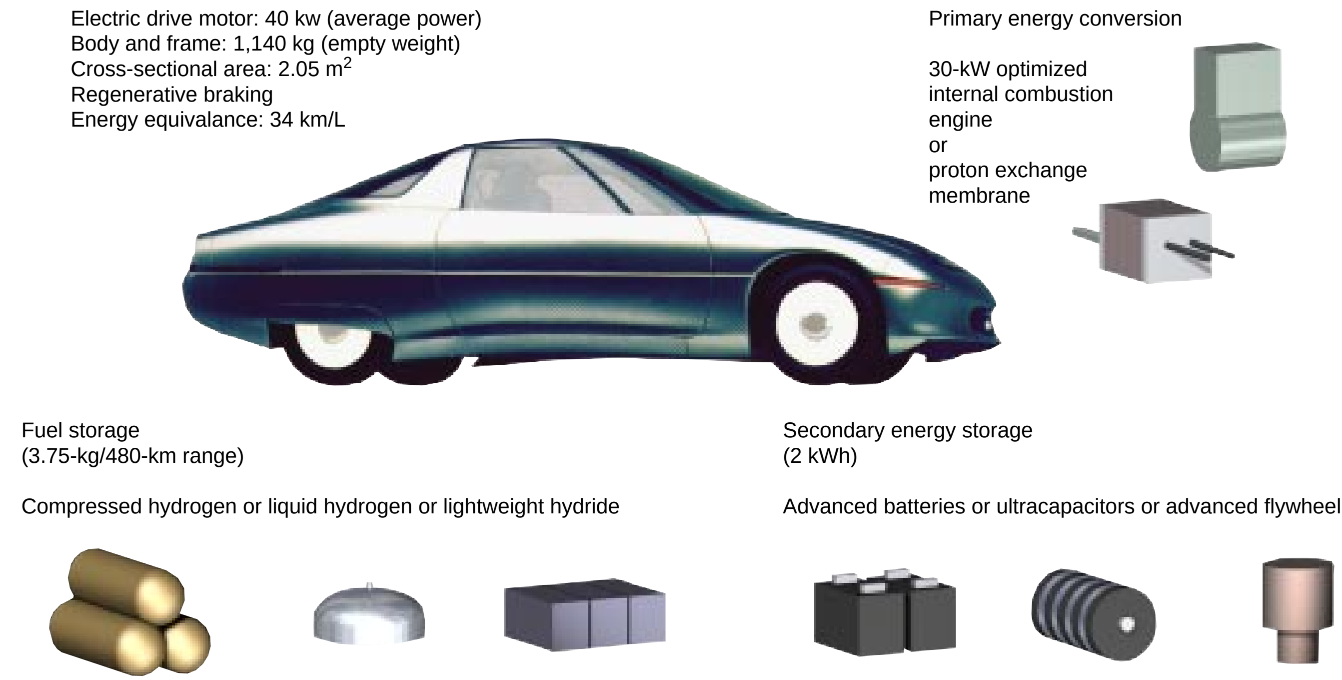


Figure 1. The Laboratory's hydrogen-fuel feasibility study based its analysis on a light-duty hybrid-electric vehicle with an internal combustion engine/generator or a proton-exchange fuel cell using hydrogen fuel in a variety of physical or chemical forms—e.g., compressed gas, cryogenic liquid, or hydrides. The vehicle has a 3.75-kg (8.3-lb) fuel storage capacity and a driving range of 480 km (300 miles) and gets gasoline energy-equivalent mileage of 34 km/L (80 mpg).

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The only significant emissions from the hybrid-electric vehicle would be water vapor and small amounts of nitrogen oxides, less than one-tenth the California ultralow-emission vehicle standards of 0.12 g/km (0.20 g/mile). Thus, this hybrid-electric car would qualify as an equivalent zero-emission vehicle.

The engine–generator combination in this vehicle achieves nearly the efficiency of a fuel cell* but at much lower cost. Until fuel cells are low enough in cost to be practical, this hybrid-electric vehicle (or one similar) would be a feasible way to begin developing the mass market and infrastructure for using hydrogen fuel for light-duty vehicles. Introducing these hydrogen-powered vehicles and developing the infrastructure to support them would ultimately facilitate and encourage the development of fuel cells.

Hydrogen Filling Stations

The study examined hydrogen fuel production and distribution—the supply and infrastructure issues at the heart of the dilemma about the feasibility of hydrogen-fueled vehicles. Its analysis showed that in the early stages of a transition to hydrogen, small-scale production and delivery options are feasible and that scaling up during the 20 to 30 years it will take to make the broader transition from gasoline to alternative fuel can be flexible and gradual should hydrogen turn out to be the alternative fuel of choice.

* A fuel cell is a means of generating electricity on board a vehicle at very high efficiency and is powered by hydrogen and atmospheric oxygen.

Table 1. A comparison of hydrogen fuel distribution technologies

Distribution technology	Vehicles supported	Economic flexibility	Relative safety	Lead time
Large pipeline (17 million kg/day)	40 million	Poor	Medium	Long
Rail	900,000	Medium	Medium	Medium
Small pipeline (100,000 kg/day)	240,000	Poor	Medium	Medium
Tanker truck	6,600	Good	Low	Short
On-site electrolysis at home or filling stations	1 vehicle to 36 million	Good	High	Short

The introduction of hydrogen vehicles does not appear to be limited by current U.S. production of hydrogen. In 1993, gaseous hydrogen production was 15.8 million kg/day (34.8 million lb/day), enough, theoretically, to fuel 44 million hybrid-electric vehicles. Currently, however, virtually all of this hydrogen is used in petroleum refining or ammonia manufacturing. Merchant hydrogen (that which is transported) accounts for a very small percentage of U.S. hydrogen production. Even so, the equivalent of today's quantities of merchant hydrogen would be enough to fuel vehicles for the first four or five years of mass production (100,000 new hydrogen vehicles per year). Hydrogen in a liquid form, currently the most cost-effective and efficient hydrogen distribution method, could fuel roughly 60,000 vehicles (using 10% of North American liquid hydrogen capacity) without additional infrastructure.

The study points out that a new hydrogen infrastructure will eventually be needed to support a mass market. However, an expansion of today's hydrogen delivery infrastructure (liquid hydrogen by truck), which is relatively expensive and energy intensive, or the construction of a hydrogen pipeline system is probably not the answer. The alternative is to develop small-scale, local hydrogen production facilities for individual consumers, vehicle fleets, and fuel stations and to make use of the electricity and natural gas distribution networks that already exist.

Table 1 compares various hydrogen distribution technologies—especially in the early stages of the transition—in terms of scale, economic flexibility, safety, and construction lead times. It shows that on-site electrolysis, using off-peak electricity and the existing electrical infrastructure, can serve a single car or up to tens of millions of vehicles. When the number of hydrogen vehicles exceeds 40 million, additional electrical capacity could be added if necessary. Approaches such as a pipeline or liquid hydrogen delivery by truck will require a large, stable hydrogen demand to justify the capital investment. Thus, the study's economic analyses suggest strongly that the transition to hydrogen can begin with small-scale production of hydrogen by off-peak electrolysis or by steam reforming at filling stations with a minimum of new infrastructure requirements and move gradually to mass-production and delivery systems.

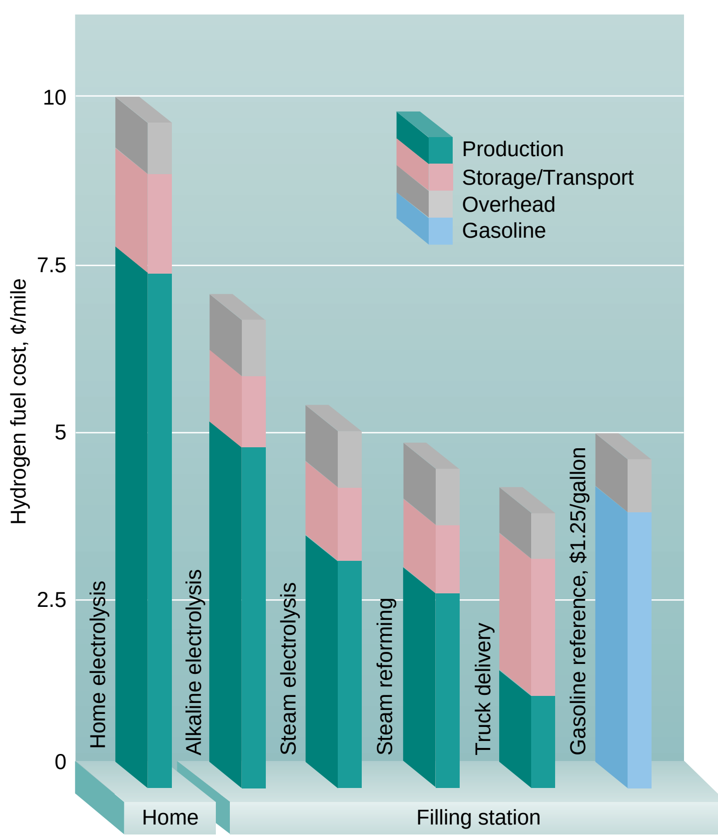

Figure 2. The per-mile cost of hydrogen fuel produced by electrolysis or steam reforming at hydrogen filling stations compares favorably with the per-mile cost for today's gasoline vehicles. (These estimates are deliberately conservative and do not include taxes on hydrogen.)

The study also developed estimates of the cost per mile of hydrogen fuel for various production, delivery, and infrastructure scenarios (see Figure 2). The 4 to 10¢/mile cost of fueling hydrogen hybrid vehicles falls within the range of gasoline costs—today's 25-mpg car at a U.S. gasoline price of $1.25/gallon requires 5¢/mile for fuel.

What About the Alternatives?

The study also compared hydrogen with other candidates to replace gasoline in alternative vehicles. The contenders, in addition to hydrogen, are electric batteries, methanol, and natural gas. Battery-powered electric vehicles would provide the highest on-board energy efficiency and, with stringent battery recycling, possibly the lowest environmental impact, but with sharp range and/or cost limitations.[3]

Hybrid-electric vehicles can surpass the limitations of batteries, but if natural gas (or methanol produced from it) are used to power hybrid vehicles, then domestic supply limitations and greenhouse gas emissions remain issues. These objections could be overcome by fueling hybrid-electric vehicles using methanol or hydrogen produced from organic waste. Methanol might be preferred over hydrogen because it is more easily stored and distributed. On the other hand, methanol is toxic, whereas hydrogen is not.

More persuasive, perhaps, is that when hydrogen is made from the same sources as methanol and used in similar ways, it has higher energy efficiency, fewer emissions, and lower environmental impact both in production and end use. Thermo-chemical conversion of municipal waste can be a sustainable source of hydrogen.[4] Electrolysis using wind or solar electricity promises to be a clean source of hydrogen fuel with even lower environmental impact than municipal waste conversion.

In comparing alternative fuels, the study concluded that hydrogen-powered vehicles could have a smoothly integrable infrastructure development and would have long-term advantages that no other fuel can match. However, it is also clear that currently there is no consensus on which fuel or fuel combination is best. Nor is there national consensus on the monetary value and relative importance of the costs that drive the search for alternative transportation fuel, that is, the need to reduce energy imports, urban air pollution, or CO_2 emissions.

And yet, people in the year 2030 will live with the consequences of alternative-fuel decisions made today. Alternative-fuel vehicles and the infrastructure to support them will need to adapt to future changes in technology and to shifts in the relative importance of economic, energy security, and environmental objectives. According to the Livermore study, hydrogen fuel seems well positioned to supply the needed flexibility to the fuel supply system of the future, and its use would ensure a single, smooth, and ultimate transition from gasoline to a clean, cost-effective alternative fuel.

Key Words: alternative vehicles, electrolysis, hybrid-electric car, hydrogen fuel.

References

1. J. Ray Smith, "This Hybrid Vehicle Uses Hydrogen," *Science and Technology Review,* UCRL-52000-95-7 (July 1995), pp. 26–27.
2. Gene D. Berry, J. Ray Smith, and Robert N. Schock, *A Smooth Transition to Hydrogen Transportation Fuel,* Lawrence Livermore National Laboratory, Livermore, CA, UCRL-JC-120152 (April 1995). These study findings were reworked for submission to *Energy: The International Journal* as Gene D. Berry, *et al., Hydrogen as a Future Transportation Fuel*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-JC-117945-Rev. 1 (June 1995), and again for the LLNL report Gene D. Berry, *et al.*, *The Feasibility of Hydrogen as a Transportation Fuel*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-JC-122167 (October 1995).
3. A Livermore advance in zinc–air fuel cells for electric fleet vehicles is featured in the October 1995 *Science and Technology Review*, pp. 6–13.
4. Lawrence Livermore scientists are exploring the use of municipal solid and other predominantly organic wastes as a feedstock for hydrogen production. With an anticipated thermal efficiency greater than 50% (heating value of hydrogen product over the heating value of feedstock), a thermo-chemical process could convert the 200 million tons of municipal waste produced annually in the U.S. to sufficient hydrogen fuel to satisfy 7% of the total U.S. transportation energy requirement. Using only half the nation's agricultural waste could satisfy the entire transportation sector. Conversion of waste to hydrogen is economically advantageous because management and disposal of wastes is expensive, and those fees become a credit against the cost of hydrogen.

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