Hype or Holy Grail? The Future of Hydrogen in Transportation

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ABSTRACT

In 1875, the great futurist Jules Verne wrote *The Mysterious Island.* [1] In one dialogue, Verne's main character, Captain Cyrus Harding, suggests that in "two hundred and fifty or three hundred years" the world would run out of coal and turn to hydrogen for fuel. The hydrogen would be produced from water "decomposed into its primitive elements" and the "coalrooms of steamers... will, instead of coal, be stored with [hydrogen and oxygen gases], which will burn in the furnaces with enormous calorific power."*

Although Captain Harding failed to anticipate the 20th century emergence of petroleum and natural gas, his prescience may finally be appreciated in the early part of the 21st. Over the past several years, clean-burning hydrogen has emerged as the "fuel of choice" for solving civilization's long-term, sustainable energy supply problems. In fact, hydrogen advocates in industry and government are promoting hydrogen as a panacea for the environmental, energy security, and natural resource dilemmas facing society.

In the transportation sector, fuel cell vehicles (FCVs) operating on hydrogen show much promise, and public funding for FCV development has followed. In the U.S., for example, the government recently committed $1.5 billion over ten years to support the Freedom Cooperative Automotive Research (Freedom CAR) initiative. Freedom CAR is aimed at developing clean, efficient, and affordable hydrogen FCVs in 10-15 years.

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*The author is indebted to Jennifer Gangi of *Fuel Cells Quarterly* for identifying this excerpt from The Mysterious Island.

However, expensive research programs cannot by themselves solve the sustainable transportation problem. If hydrogen is to ever achieve significant market penetration, then coordinated, systematic market development is needed. This article considers the opportunities and barriers facing hydrogen's emergence in future transportation markets. Although the article focuses mainly on the United States, the discussion applies readily to situations in other countries.

TRANSPORTATION AND SUSTAINABILITY

Captain Harding's prediction mentioned above illustrates the Malthusian view that non-renewable resources, like coal, can't last forever. A more contemporary example of this attitude was extended in the 1970s when the Club of Rome published *Limits to Growth. Limits to Growth* argued that resource depletion, population growth, and environmental deterioration could choke economic growth in the early 21st century. [2] Similar arguments have been refined and articulated by many neo-Malthusians in the early part of the 21st century within the context of "sustainable development." [3, 4]

Within this context, the role of the transportation sector takes on primary importance. Transportation is associated not only with the consumption of a nonrenewable energy source—in the U.S. over 96% of transportation energy use is derived from petroleum [5]—but also with calamitous environmental problems, including global warming, local air pollution, and water pollution. With the continued growth of petroleum-based transportation in countries like China and India, there is grave concern that we will soon face critical energy shortages or environmental cataclysm. [6]

In the U.S., although personal transportation vehicles are much cleaner than three decades ago, transportation still contributes a significant share of emissions, as shown in Figure 1. These contributions are largely due to the increased level of driving that has occurred in the U.S. over the past 30 years, shown in Figure 2.

A nation's dependence on petroleum also raises energy security concerns. The U.S. transportation sector accounts for two-thirds of all petroleum consumed in that country, over 50% of which is imported. This continued reliance on foreign oil, along with flat domestic production, has created a "transportation oil gap," shown in Figure 3. In

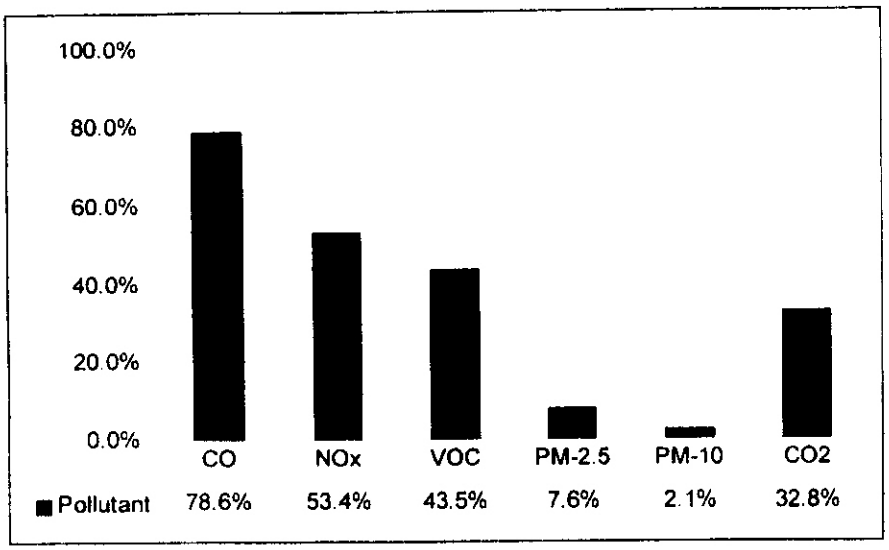

Figure 1. U.S. Transportation Emissions as Percentage of Total (1999)

Source: [5], Tables 3.3 and 4. 1.
Notes: CO = carbon monoxide; NO_x = oxides of nitrogen; VOC = volatile organic compounds; PM-2.5 = particulate matter with aerodynamic diameters 2.5 microns or less; PM-10 = particulate matter with aerodynamic diameters 10 microns or less; CO_2 = carbon dioxide.

2000, the transportation oil gap accounted for over $45 billion of the U.S. trade deficit alone, and this number is expected to exceed $100 billion by 2020 (in 2000 dollars). In addition, it is estimated that the U.S. spends between $6 billion and $60 billion dollars annually (1996 dollars) in military expenditures associated with defending oil supplies in the Middle East. [5]

THE EMERGENCE OF HYDROGEN

The convergence of environmental, energy security, and resource issues has created a strong desire by government to diversify transportation fuels. For example, in the U.S. the passage of the Energy Policy Act of 1992 (EPACT) was intended to lead the country towards

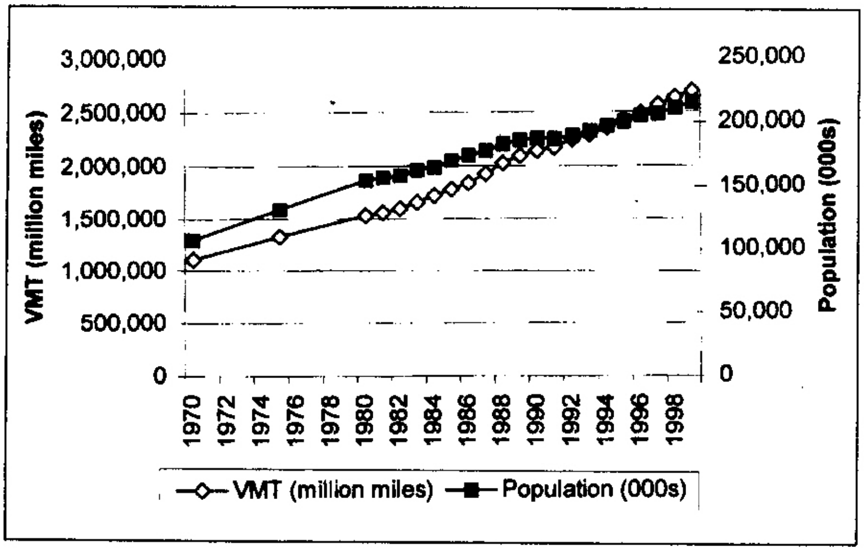

Figure 2. U.S. Vehicle Population and Vehicle Miles Traveled (VMT) Trends—1970-1999

Source: [5], Tables 6.3 and 6.5.

a less petroleum-dependent transportation sector. [8, 9] EPACT did this through mandates and incentives that encouraged the use of alternative fuel vehicles (AFVs, or vehicles operating on "substantially non-petroleum based fuels" such as natural gas or ethanol).

The success of EPACT and similar policies has been limited, as shown in the relatively slow growth and even stagnation of U.S. AFV populations (see Figure 4). Today's AFV populations are much lower than projections from the early 1990s; for example, the 2001 AFV population is slightly over 450,000, whereas EPACT goals implied achieving AFV populations of several million vehicles by 2000). [9]

Despite the lack of widespread success of AFV markets, hydrogen shows promise as a "next-generation" alternative fuel. Many modem day soothsayers are predicting that hydrogen will become our "fuel of choice" in the next 20-50 years. [10, 11] The energy and environmental benefits of this fuel are significant. Hydrogen, when combined with oxygen in a FCV, generates electricity that powers an electric drive propulsion system. The by-product of the hydrogen-oxygen

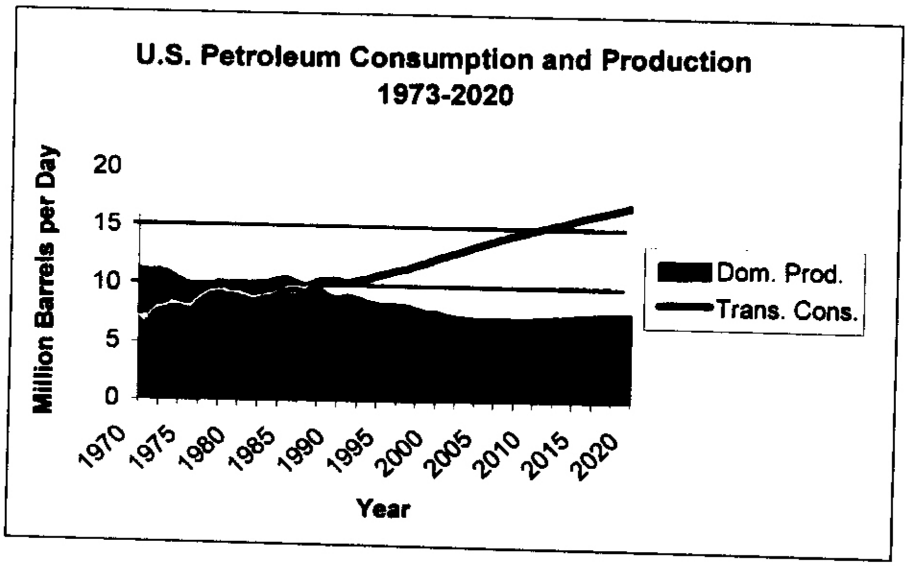

Figure 3. Transportation Oil Gap, 1973-2020

U.S. Petroleum Consumption and Production
1973-2020

Sources: [5, 7]
Notes: Dom. Prod. Domestic production of crude oil in the U.S. in million barrels per day; Trans. Cons. = Transportation consumption of crude in million barrels per day.

reaction is water, and so noxious tailpipe emissions in a pure-hydrogen FCV are eliminated. In addition, hydrogen can be produced through the electrolysis of water. If electrolysis is performed using renewable energy technologies such as solar or wind power, hydrogen would represent an unlimited, clean source of domestic fuel for transportation.*

*The technical issues associated with hydrogen fuel cell systems, hydrogen production through electrolysis, and hydrogen production through other mechanisms is beyond the scope of this article and can be found elsewhere. 12. Winebrake, J.J. and B.P. Creswick, *The Future of Hydrogen Fueling Systems for Transportation: An Application of Perspective-Based Scenario Analysis Using the Analytic Hierarchy Process*. Technological Forecasting and Social Change, 2002.

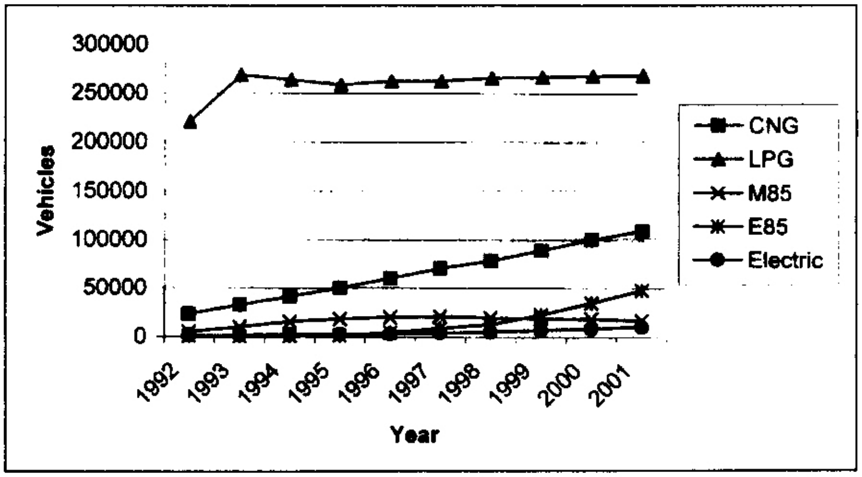

Figure 4. AFV Populations by Fuel Type, 1992-2001

Source: [5], Table 9.1.

Events of the past year or two portend that hydrogen optimists may be onto something. Consider the following events of 2001 and early 2002:*

- All major auto companies demonstrated FCV prototypes, with some like General Motors, Ford, and Honda announcing plans to release hydrogen fuel cell models in the 2004-2006 time frame.
- DaimlerChrysler announced it would produce a hydrogen fuel-cell minivan that uses a hydrogen storage system that will reduce the costs and increase onboard storage capacity.
- Ballard Power, a major fuel cell company, completed a demonstration project that incorporated a hydrogen fuel cell bus in the SunLine Transit Agency (Thousand Palms, CA) fleet. The bus accumulated about 15,000 miles over a thirteen-month period.

*Most of the items in this list were selected through review of monthly editions of the electronic *Fuel Cell Technology Update* produced and distributed by Jennifer Gangi of Fuel Cells 2000 (*http://www.fuelcells.org*).

- Ford set a record by driving its P2000 fuel cell vehicle 1,390 miles over a 24-hour period at an average speed of about 58 mph.

- Toyota demonstrated a 63-seater, low-floor city fuel cell bus that carries high-pressure tanks of hydrogen to fuel a fuel cell system.

- General Motors presented its AUTOnomy fuel cell vehicle, built upon a "skateboard chassis" that allows flexibility of design that can revolutionize how we think about personal transportation technologies.

Hydrogen's potential also has Wall Street giddy, and an outsider would have thought that by early 2000 hydrogen was ready to compete head-on with gasoline. One could say a hydrogen bubble was formed in early 2000, as shown in Figure 5. Since that time hydrogen stocks have returned from the stratosphere.

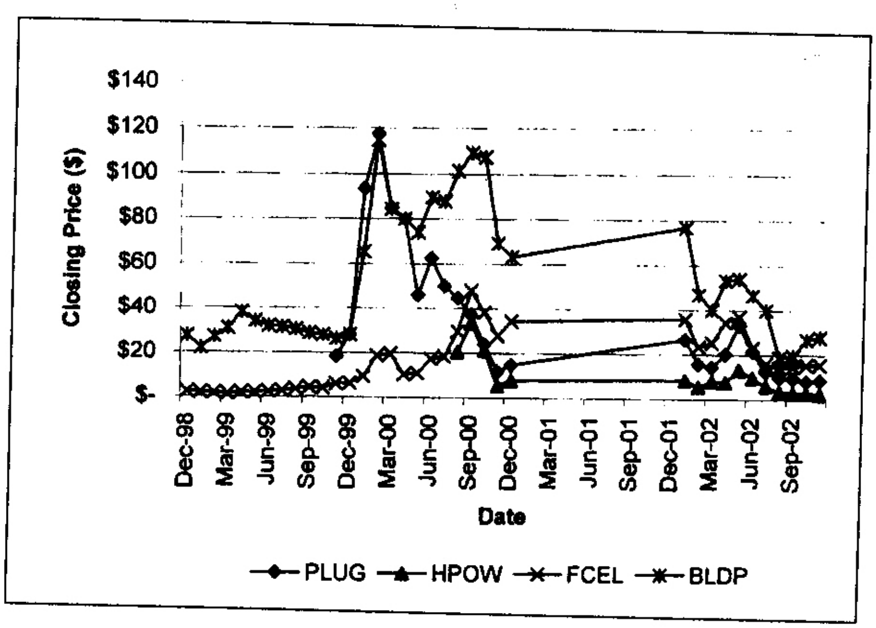

Figure 5. Closing Prices for Selected Hydrogen Stocks

IMPORTANT CRITERIA FOR SUCCESS

However, before we anoint King Hydrogen, we must consider the realities of the transportation marketplace. Petroleum dominates that marketplace and presents hydrogen with a formidable, well-entrenched opponent. By reviewing past attempts to introduce other alternative fuels in the market, we can identify some of the barriers that hydrogen will have to overcome.

Table 1 presents a list of criteria by which hydrogen (and other fuels) can be evaluated with regards to competition with conventional fuel and vehicle systems. These criteria can help us evaluate the market potential for hydrogen.[12] The criteria are grouped into five larger categories: (1) Fuel production and distribution; (2) Vehicle operation and performance; (3) Environmental impacts; (4) Resource issues; and, (5) Economic issues). For hydrogen to compete with petroleum, hydrogen must rank favorably in many of these categories, especially categories #1, #2, and #5.

In addition to these criteria, a review of our past experiences with other alternative fuels can provide guidance on hydrogen market potential. Some applicable lessons include:

1. *Progress will be slow.* The transition from petroleum to hydrogen will take many decades. Even the U.S. Department of Energy's Energy Information Administration (EIA) has recognized the "rootedness" of the gasoline vehicle in American society, estimating that by 2020, only 130,000 light-duty FCVs (primarily operating on hydrogen derived from gasoline on-board the vehicle) will be in the market.* This represents about 0. 05% of the 264 million light-duty vehicles that are expected to be on the road at that time. [7]

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*Reforming is the chemical process by which hydrogen is produced from a hydrocarbon. This can be done "off-board," for example at a large merchant hydrogen facility that produces hydrogen from natural gas; or it can be done "on-board," for example using a small system under the hood of the vehicle that generates hydrogen from a hydrocarbon (e.g., gasoline) and then feeds the hydrogen to the fuel cell stack. The off-board system is less complex, and thus cheaper; but one must find a way to distribute the hydrogen. The on-board system is more complex and thus more expensive; but affords much greater availability of fuel.

Table 1. List of Criteria for Evaluating Hydrogen Market Potential

Criteria	Description
(1) Fuel production and distribution	
Production capacity	The availability of fuel feedstock and production capacity.
Safety and health	Health and safety issues associated with fuel production and storage.
Refueling convenience	A measure of fueling access through adequate refueling stations.
(2) Vehicle Operation and Performance	
Start-up time	The time that it takes for fuel cell systems to provide enough energy to allow for vehicle propulsion.
Range	The distance (in km) a vehicle can travel on a full tank of fuel.
Peak power	The maximum power output (in kW) a vehicle can attain from the system.
Safety	Safety of the on-board fuel system.
Transient response	The time delay between depression of the accelerator and vehicle response.
(3) Environmental Impacts	
GHG emissions	Emissions of greenhouse gases (GHGs) along the entire fuel cycle.
Local pollutants	Emissions of local and regional pollutants, including particulate matter (PM), oxides of nitrogen (NO_x), carbon monoxide (CO), and hydrocarbons (HC).
Land use	A measure of the land use impacts associated with hydrogen infrastructure.
Distribution	The environmental impacts of upstream activities, including environmental impacts of producing, transporting, storing, and distributing the fuel.
(4) Resource Issues	
Foreign dependence	A measure of the level of hydrogen feedstock that must be imported.
Sustainability	A measure of feedstock supply over a long period of time (40-70 years), in amounts sufficient for supplying large market penetration.
(5) Economic Issues	
Vehicle costs	The capital cost of the vehicle, including processor and storage systems.
Operational costs	The costs seen by consumers for maintenance and fuel (in cents per mile).
Infrastructure costs	The costs associated with building the hydrogen refueling infrastructure.

Source: Adapted from [12].

2. *Infrastructure issues will be the thorn in the side.* Soon after EPACT was passed (October 1992) government officials adopted Say's Law with respect to AFV markets: "Build it and they will come!" With respect to AFVs, the "it" was infrastructure (refueling stations) and the "they" were AFVs. Much time, effort, and money was invested into infrastructure development. However, compared with gasoline, sparse AFV fueling stations increased the "convenience costs" associated with AFV ownership. (Convenience costs are primarily due to increased time associated with traveling to an AFV station, but could also be costs associated with decreased ranges and lack of maintenance services.) The result has been stranded refueling station investments in many parts of the country. The lesson we learn is to never underestimate convenience costs—infrastructure development must provide FCV owners equal or even reduced convenience costs compared to gasoline. "At-home refueling" is one such possible approach (see below).

3. *Benefits depend on feedstock choice.* Hydrogen can be produced from any number of hydrocarbon fuels. Fuel processors currently exist to extract hydrogen from natural gas, methanol, ethanol, propane, and gasoline. However, each extraction process faces its own environmental, energy security, and economic issues.[12] We must be careful we don't select a FCV technology path involving large investments, yet producing very limited energy security and environmental benefits compared to high-efficiency, low-emissions gasoline vehicles, electric vehicles, or hybrid-electric vehicles.

4. *FCV costs must be less than today's conventional vehicle costs.* Despite predictions that oil production will peak in the next 10 years [6] and significant price increases will follow, there is little historical evidence to suggest this will happen. Oil prices have remained relatively flat over the past several decades, largely due to advanced extraction technologies and new field development. The best strategy for hydrogen proponents is to envision a future in which conventional fuel and vehicles are priced similar to today's prices, and to work to reduce the cost of hydrogen and FCVs to that point or less. There are a number of estimates of how hydrogen may be produced and delivered in the near future at costs

competitive or even less than gasoline. [13, 14] Vehicle costs are expected to be about $2,000 more for a pure hydrogen fuel cell vehicle without on-board reforming (on-board reforming would add another $2,000 or so). [14] These costs must come down, unless FCVs can provide other auxiliary benefits (see below) to vehicle owners.

5. *Government policies must be clear and enforceable.* Government policies to promote AFVs have had mixed results. Federal mandates and incentives in EPACT have arguably failed, as purchase requirements for fleet operators were never enforced and purchase incentives proved too small. State policies to promote AFVs, such as the zero-emission vehicle (ZEV) mandates in California and New York have also had their implementation delayed, sending a strong message to auto manufacturers and fuel providers that government regulations are "optional." If government chooses to support hydrogen development for the social benefits this fuel provides, then policies must be clearly stated and enforced.

6. *Auxiliary benefits must be enhanced.* Hydrogen FCV markets would be augmented greatly if auxiliary benefits of FCV ownership could be exploited. For example, some researchers have proposed so-called "vehicle-to-grid" capabilities for FCVs that would allow vehicles to "plug-in" to the utility grid and provide electricity services to the utility. The utility would pay for these services, which include peak power production, spinning reserves, and power quality management options.[15] Another example of auxiliary benefits is seen in General Motor's AUTOnomy concept vehicle. Because the fuel cell system on AUTOnomy is embedded in a common "skateboard chassis," consumers would have the option of custom designing the vehicle that rests on that chassis. This may include custom placement of seats, accessories, steering mechanism, cargo space, and frequent inter-changeable body types. Finally, since hydrogen can be produced at home via a natural gas reformed, "at-home" refueling could add another auxiliary benefit. With these auxiliary benefits, consumers may be more willing to pay extra for a FCV, and a FCV providing these benefits would, *ceteris paribus,* be more attractive than a conventional vehicle.

CONCLUSIONS

Hydrogen may indeed represent energy's Holy Grail, providing unlimited amounts of clean energy in the future. However, a smooth transition from fossil fuels to hydrogen should not be expected. Many opportunities exist, but many barriers must be overcome. Our past experience with other alternative fuels has identified some of these opportunities and barriers, including costs, infrastructure development, government policies, and auxiliary benefits.

We must be cautious of the "hydrogen hype" now voiced by many in government, industry, and the media. Such hype would be harmless if it were not for the fact that resources are limited and hydrogen puffery may take away from devoting resources to alternative means of providing transportation services. For now we must make a realistic assessment of a hydrogen future, and compare that future with others based on different technologies and fuels.

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