REPP ISSUE BRIEF
APRIL 1997 ◦ NO. 7

Clean Hydrogen Transportation: A Market Opportunity For Renewable Energy

James S. Cannon

Executive Summary

Advocates of renewable energy technologies must develop market entry strategies to move the world more rapidly toward a sustainable energy economy. This paper examines an exciting market opportunity that will help achieve that goal: renewables-based hydrogen vehicles. Hydrogen-powered fuel cells used in place of conventional gasoline- and diesel-fueled internal combustion engines would significantly reduce automotive air pollution. Shifting from oil to hydrogen to power U.S. cars also would bolster national energy security. The policy environment for this shift is favorable as public programs to promote alternative fuels are increasing. Further, much of the infrastructure is in place since technologies for natural gas vehicles are similar to the technologies that will be needed in a hydrogen-based transportation system. While hydrogen cars are in the early stages of development, the economics of renewable transportation are improving steadily. Economically competitive hydrogen vehicles, once they reach the market, should find a receptive audience among green consumers.

James Cannon is President of Energy Futures, an energy and environmental consulting firm based in Colorado. He is also Senior Energy Fellow for INFORM, an educational organization specializing in transportation issues. From 1991 to 1994, he served as New Mexico's Energy Policy Project Director. He may be contacted at PO Box 4367, Boulder, CO 80306; (303) 541-0185; jscannon@msn.com.

REPP ISSUE BRIEFS MAY BE ORDERED FROM THE EDITOR, SUSAN CONBERE, AT 301-405-4550; OR E-MAIL SCONBERE@BSS2.UMD.EDU.

A Message From the Renewable Energy Policy Project

Many advances in renewable energy involve electricity-producing technologies designed for connection to the transmission grid. These advances include windfarms, plants fueled by agricultural waste, and residential photovoltaic panels, among others. In the following paper, consultant James Cannon outlines a role for renewable energy in the transportation sector. Mr. Cannon proposes hydrogen as an automotive fuel. This clean-burning gas could be produced by electrolyzing water with current generated by renewable energy technologies, direct photochemical or photobiological conversion, or biomass gasification.

Deployment of renewables in the transportation sector makes sense for the environment. Road vehicles emit significant air-borne pollution, including 18% of America's suspended particulates, 27% of volatile organic compounds, 28% of lead, 32% of nitrogen oxides, 37% of formaldehyde, 45% of benzene, and 62% of carbon monoxide. Vehicles also release 25% of America's energy-related carbon dioxide, the principal greenhouse gas. These figures will rise as Americans travel ever more vehicle-miles. World pollution levels will grow even faster as millions of people gain access to public and personal transportation.

In addition to cutting vehicle emissions, renewable hydrogen also can reduce America's oil dependence. Although utilities have largely ceased burning oil since the shortages of the 1970s, most American automobiles, trains and airplanes depend on it. This dependence leaves the nation vulnerable to economic shocks—and human suffering—should political events again jolt the world oil market. A renewable energy transportation sector would be partially insulated from such shocks.

Unlike the electric sector, where consumers are unaccustomed to shopping for power, Americans are used to making complex choices in the transportation sector. They select a specific automobile from dozens of models, and many people see cars as a statement about lifestyle. The transportation sector represents an arena in which canny marketers of clean energy can take advantage of increasing enthusiasm for environmental protection without having to teach consumers how to shop for their product.

Achieving sustainable transportation will require effective planning and robust public transportation, in addition to the identification of plentiful clean fuels. Yet, several energy analysts view renewable-hydrogen as the ideal fuel on which to base the economy of the future. We are glad to present Mr. Cannon's contribution to that ongoing debate.

We thank Mr. Cannon for his effort in preparing this provocative piece, and Susan Conbere for her editorial contribution.

Adam Serchuk & Alan Miller **April 1997**

CLEAN HYDROGEN TRANSPORTATION: A MARKET OPPORTUNITY FOR RENEWABLE ENERGY

James S. Cannon

Every half-hour more solar energy strikes the Earth than is released globally by the burning of all fossil fuels in a year. Although only two-billionths of the sun's energy reaches Earth, there is more than enough sunshine and other forms of renewable energy to supply the world's energy needs for centuries. The globe is now in transition from the renewable energy past, where sunshine captured in food and wood provided most of the world's energy, to a renewable energy future, where pollution-free energy carriers—electricity and hydrogen—increasingly will be used to capture, store, and distribute renewable resources in a sustainable energy economy.

A critical challenge facing renewable energy advocates today is to develop market entry strategies capable of propelling the world as quickly as possible into the post-fossil era. To succeed, these strategies must resolve the following problems: (1) technological challenges facing renewable industries; (2) initial high costs of manufacturing advanced technologies in low-production volumes; (3) difficulties in deploying energy systems without a fully-developed fuel production or distribution infrastructure; and (4) the opposition of some of the most powerful corporations in the world, which staunchly defend the status quo.

This paper examines a market entry opportunity for renewable resources in the transportation sector.[1] The end game is to replace the conventional gasoline- and diesel-fueled, internal combustion engine-powered vehicles with electric vehicles that are equipped with fuel cells and powered by hydrogen produced from renewable resources. A market entry in transportation using this strategy could provide an important complement to ongoing efforts to introduce renewable resources into centralized electrical power generation. It also offers an exciting avenue toward sustainable transportation that can work in concert with other strategies. These strategies include increased use of mass transit and alternative transportation modes, stricter fuel efficiency and tailpipe emission standards, and implementation of a wide range of transportation demand management programs designed to reduce vehicle miles traveled.

This brief begins with a discussion of the shift toward fossil fuels in the 20th century and the need to alter this course. The paper proceeds to a more technical discussion of renewables-based hydrogen as a source of sustainable energy for the transportation sector. Six reasons are given for why renewable energy advocates should pursue market entry opportunities for renewables-based hydrogen vehicles. The paper concludes with five recommendations for developing a market entry strategy.

---

[1]Much of the analysis of transportation issues and use of hydrogen that appears in this paper is developed in greater detail in J. Cannon, *Harnessing Hydrogen: The Key to Sustainable Transportation* (New York: INFORM, Inc., 1995). The research for this brief included conversations or interviews with the following energy specialists: Ashok Gupta, Natural Resources Defense Council; John Nielsen, the Land and Water Fund of the Rockies; Bruce Driver, legal consultant specializing in electric utility issues; New Mexico Public Utility Commissioner Lawrence Ingram; John Curl, Executive Director of the New Mexico PUC; Nicholas Lenssen, E Source; and Chris Flavin, WorldWatch Institute. The author also wishes to thank John DeCicco, Rachel Finson, Peter Hoffman, Jason Mark, Alan Miller, and Adam Serchuk for their comments.

The Global Energy Transformation

The widespread availability of fossil fuels during the 20th century has permitted an unprecedented growth in energy availability—from the meager supplies obtainable from food and wood to today's vastly larger energy supply of coal, oil, and natural gas.

The success of fossil fuels in the marketplace has occurred largely because of their ability to address the most vexing attributes of renewable energy, which is diffuse, intermittent and found in forms (such as photons) that are difficult to use in modern machines. Nature's work over millennia to compress and chemically transform prehistoric organic debris has produced fossil fuels that are rich in energy, easy to store and transport, and readily useable on a large scale.

Coal and natural gas provide more than 65% of the energy used to generate electricity in the United States; oil fuels virtually all U.S. vehicles. In contrast, renewable energy provides less than 2% of the energy used in either market.

Electrification of our energy economy and the rise of automotive transportation are two of the most significant technological revolutions of the 20th century, exemplifying the massive change in lifestyle due to the growth in fossil energy supplies. From negligible energy markets in 1900, electrical generation now accounts for 34% of primary energy consumption in the United States, while transportation consumes 27% of our energy supply.[2] Increased fossil fuel use has financed both energy expansions: coal and natural gas provide more than 65% of the energy used to generate this nation's electricity, while oil fuels virtually all the 190 million vehicles now cruising U.S. roadways. Renewable energy, however, provides less than 2% of the energy used in either market.[3]

The electricity and transportation energy revolutions of this century have, to date, affected different and largely non-overlapping markets. Electricity is used extensively in the commercial, industrial, and residential sectors, but it supplies barely a blip of energy to transportation markets. On the other hand, oil is not a heavy hitter in electrical generation, now contributing a mere 3% of energy input for electricity.[4] Oil use in transportation, however, is huge and growing. More than two-thirds of the oil consumption in the United States is used in transportation, mostly to power cars, trucks, and buses. Aircraft account for about 14% of transportation oil consumption, while locomotives and ships are the chief consumers of the remaining

---

[2]U.S. Energy Information Administration, *Annual Energy Review 1994* (Washington, DC, Jul. 1995), 9.

[3]*Annual Energy Review 1994*, 235. Renewable energy as used in this paper includes direct solar, wind, biomass, non-conventional hydropower and geothermal resources. Wood and municipal waste burning (biomass) and geothermal energy, about 80% of which is produced by non-utility generators, comprise nearly all of the electricity currently generated from these renewable resources. Renewable energy use in road transportation is minimal. Ethanol obtained mainly from corn fermentation constitutes about 1% of the fuel used in automobiles, but the heavy use of fossil fuels by current agricultural practices renders ethanol non-sustainable as now produced. *Annual Energy Review 1994*, 231, 265.

[4]*Annual Energy Review 1994*, 137.

5%.[5] Annual oil use in the transportation sector alone has surpassed total domestic oil production every year since 1986.[6]

Continued reliance on fossil fuels either for electrification or transportation cannot continue into the indefinite future. The world is currently using fossil fuels 100,000 times faster than they are being recreated by natural forces.[7] As readily exploitable reserves are consumed, the remaining fossil resources become more costly and difficult to extract. Using the remainder will have troubling political and social repercussions and disturbing environmental consequences, such as global climate change, that threaten the existence of life on Earth.

Completing the energy transformation that began a century ago requires shifting from fossil fuels to sustainable energy systems. This transformation demands the development of energy systems capable of manufacturing energy carriers directly from renewable energy resources, avoiding the detour through fossil fuels.[8] It took nature eons to create fossil fuels, whereas in just a few years, renewable resources must be captured, concentrated, and stored in energy carriers in sufficient quantities to supply energy end use markets effectively.

Hydrogen: A Viable Sustainable Energy Carrier for Transportation

Electricity is one energy carrier that can be produced sustainably from renewable resources. Commercial power plants now convert solar, wind, biomass, and geothermal energy directly into electricity. Taken together, these renewable resources now supply over 15,000 megawatts to the nation's electrical grid.[9] Once generated, electricity can be moved through transmission lines and used in a wide variety of energy applications without producing pollution.

In 1900, electric cars outnumbered gasoline vehicles by a factor of two to one; nearly a century later, electric cars are making a comeback.

---

[5] U.S. Energy Information Administration, *State Energy Data Report, 1993* (Washington, DC, Jul. 1995), 15.

[6] *Annual Energy Review 1994*, 139, 159.

[7] C. Steinhart, and J. Steinhart, *Energy: Sources, Uses, and Role in Human Affairs* (North Scituate, MA: Duxbury Press, 1974), 112.

[8] There is an extensive literature analyzing full fuel cycle energy systems, including the various steps in the conversion of primary energy resources into intermediary energy carriers capable of powering end use technologies that provide energy services. A particularly lucid analysis of the "architecture" of energy systems, which discusses hydrogen as well as electricity as attractive energy carriers for renewable energy, is D. Scott, "Hydrogen in the Evolving Energy System," *International Journal of Hydrogen Energy* 18 (Mar. 1993).

[9] *Annual Energy Review 1994*, 231.

Unfortunately, little progress has been made in using electricity generated from this centralized power grid in transportation, despite a promising beginning a century ago. In 1900, electric cars outnumbered gasoline vehicles by a factor of two to one; an electric race car held the world land speed record. Their quiet, smooth ride and the absence of difficult and dangerous hand-crank starters made electric vehicles the car of choice, especially among the urban social elite. Early in this century there were more than one hundred electric vehicle manufacturers.[10]

The weight, space requirements, long recharging time, and poor durability of electric batteries undercut the ability of electric cars to compete with much more energy-dense gasoline, an energy carrier manufactured from crude oil. One pound of gasoline contained as much chemical energy as the electricity held in one hundred pounds of the lead acid batteries then in use. Refueling a car with gasoline was measured in minutes, on-board storage was a snap, supplies appeared to be limitless, and long-distance fuel delivery was relatively cheap and easy. With these attributes, gasoline dominated the fuel marketplace. By 1920, electric cars had virtually disappeared.

As environmental and resource depletion issues take their toll on the oil-dominated transportation system nearly a century later, electric cars are now making a comeback. In December 1996, General Motors began selling the EV-1, the first electric car to be produced by a major automotive manufacturer in more than 70 years. Hundreds of other companies worldwide have spent the last decade in frenetic electric vehicle research, development, and commercialization. The critical issues of battery weight, volume, and recharging, however, continue to present major obstacles to the commercial success of vehicles recharged with electricity from a grid. These impediments thwart attempts to bring renewable energy resources into the transportation marketplace through a connection to centralized power generation.

Hydrogen releases three times more energy per pound than burning a pound of gasoline or natural gas, and six times more energy than burning a pound of coal.

[10]An entertaining history of electric vehicles is M. Schiffer, *Taking Charge: The Electric Automobile in America* (Washington, DC: Smithsonian Institution Press, 1994). The topic is also discussed in J. Cannon, *Harnessing Hydrogen: The Key to Sustainable Transportation* (New York: INFORM Inc., 1995), chapters I, III.

Hydrogen is another carrier of energy that, like electricity, can be produced from various renewable and nonrenewable resources. It offers an alternative to electricity generated at centralized powerplants. Hydrogen also displays many of the attributes of centrally generated electricity and minimizes most of the problems of using centrally generated electricity in transportation applications. Molecular hydrogen (consisting of two bonded hydrogen atoms) is a potent fuel, containing three times more energy per pound than gasoline and six times more energy per pound than coal. About 93% of the known universe consists of hydrogen atoms, but most of the hydrogen on Earth appears in combination with other elements. Just as electricity is generated from the energy in other resources, molecular hydrogen is produced by extracting hydrogen atoms from compounds that contain other elements.

Once manufactured in pure form, the energy in hydrogen can be released by burning or it can be converted without combustion to electricity in fuel cells. An electrochemical device with no moving parts, a fuel cell uses catalysts, electrodes, semi-permeable membranes and electrolytic substances to control the combination of hydrogen and oxygen to form water. The energy released by the chemical reaction is captured electrochemically as electricity. Because no combustion occurs and little of the chemical energy escapes as waste heat, fuel cells are highly efficient electrical generators. Efficiencies of 50% are achievable today. Emerging fuel cell technologies should surpass 60% efficiency rates. These efficiencies compare to those of an automotive internal combustion engine, which currently converts less than 20% of the energy in gasoline into motion. Although invented in 1839, fuel cells were not developed commercially until the 1960s, when their suitability for generating electricity aboard space craft was recognized. Every space vehicle in the Apollo, Gemini, and Shuttle space programs has been powered in part by hydrogen fuel cells.[11]

Whether the energy in hydrogen is released as heat through combustion or converted into electricity in a fuel cell, little or no pollution is produced when the chemical energy in hydrogen is tapped. The sole byproduct of the chemical combination of hydrogen and oxygen is water. No carbon dioxide, hydrocarbons, carbon monoxide, sulfur compounds or toxic air pollutants are released. Because they operate at low temperatures, fuel cells also produce no nitrogen oxides. Hydrogen combustion produces some nitrogen oxide air pollution because of the high temperatures involved. Tests to date indicate that nitrogen oxide concentrations from hydrogen-burning engines can be kept very low, meeting the proposed California equivalent zero emission vehicle standard.

Air pollution from hydrogen production is potentially very small as well. If fossil fuels are used in the hydrogen production process, as they are in the steam reforming of natural gas (discussed below), then some environmental impacts could be associated with the production, processing, distribution of these fossil fuels. The major environmental problems associated with hydrogen produced from renewable resources are due to the materials used in technologies to produce hydrogen, or in the fuel cells that use these materials. Carcinogenic asbestos membranes and potent potassium hydroxide, for example, are currently used in hydrogen-generating electrolyzers. Other environmental concerns stem from land use considerations

---

[11]Five types of fuel cells are now under development. The proton exchange membrane fuel cell is best suited for transportation applications. Most prototype fuel cell vehicles are outfitted with proton exchange membrane technology. Other technologies are the phosphoric acid, alkaline, molten carbonate, and solid oxide fuel cells.

associated with large-scale renewable resource development, and with air and water pollution from biomass production and use.

Furthermore, a variety of toxic metals are used as catalysts or electrodes in some advanced hydrogen production technologies and in fuel cells. Recovery and reuse of these expensive materials is important to improving the economics of these technologies, however, so that zero environmental damage can be achieved in most cases.

Hydrogen Production

Currently, nearly all the hydrogen produced in the world is, like electricity, derived from fossil fuels. In the case of hydrogen, steam reforming of natural gas is the most common production method. In this reaction, natural gas and water are mixed at moderate temperatures and pressures in the presence of catalysts. Both molecules dissociate under these conditions to form a mixture of hydrogen, carbon monoxide, carbon dioxide, and other gases. This mixture of "synthesis" gases is fed into a second reaction chamber where a "shift reaction" with additional steam takes place. The result is a nearly complete conversion of the gases into hydrogen and carbon dioxide. Steam reforming energy efficiencies above 70% are common. Partial oxidation and pyrolysis are other, less typical, methods of chemically reformulating hydrocarbon fuels and water into hydrogen and carbon dioxide. As with steam reforming, natural gas is normally the energy feedstock in these reactions, although coal and oil can be used as well.

Like electricity produced from fossil fuels, hydrogen produced from natural gas or other fossil fuels is unsustainable because supplies are limited. Also, the processes, though clean compared to oil refining or electricity generation from coal, are not pollution free. The reactions produce carbon dioxide and trace concentrations of carbon monoxide, hydrocarbons and nitrogen oxide.

The most commonly used method of hydrogen production, after steam reforming of natural gas, is electrolysis of water. In this process, an electrical current passes through electrodes immersed in an electrolytic solution divided into two chambers by a semi-permeable membrane. The electrical energy splits the water molecule into hydrogen and oxygen gases, which are released and collected at the electrodes. Energy efficiencies in electrolysis generally exceed 80%; the process produces no air pollution.

Electricity produced from any source is indistinguishable in its ability to provide the energy to produce hydrogen through electrolysis. Therefore, any renewable resource that can be used to generate electricity is capable of producing hydrogen through electrolysis. In California today, there are two hydrogen vehicle demonstration facilities, one at the University of California at Riverside and one at a Xerox Corporation facility in El Segundo. Both employ photovoltaic cells to generate electricity to power electrolysis units that manufacture hydrogen. Two other photovoltaic fields are used to generate hydrogen in Germany. A handful of other plants exist elsewhere. A project underway in Palm Desert, California will use windpower to provide the electricity to manufacture hydrogen for use in a fleet of small personal utility vehicles.

There are various other methods to produce hydrogen directly from renewable resources without the intervening step of electrical generation. Although none of these technologies is in commercial application, bench-scale or demonstration-scale plants show them to be capable of producing hydrogen sustainably and

with little or no environmental impact. Research is underway at multiple sites worldwide to develop and commercialize the following direct hydrogen production technologies:

- **Biomass or municipal waste gasification**: One direct method of producing hydrogen involves the gasification of municipal waste or biomass, such as fast growing grasses or trees, to extract hydrogen. Biomass or municipal waste gasifiers are similar to the systems that have been developed to gasify coal as part of integrated gasification, combined cycle power generators. The technology can be completely renewable resource-based if biomass or renewable waste is used to provide the heat needed to power the gasification process and the feedstock that is gasified. Because biomass gasification relies on technology that has been developed for other applications, it is the most advanced of the direct approaches to hydrogen production. Although more costly compared to the cost of conventional steam reforming of natural gas, biomass gasification is the least expensive and one of the most promising methods of direct hydrogen production from renewable resources.

- **Direct photoelectrochemical conversion**: In photochemical systems, sunlight strikes an electrolytic solution in which photosensitive semiconductors and catalysts are suspended. The solar energy is absorbed by the catalysts, creating localized electrical fields that trigger the electrolytic splitting of water into hydrogen and oxygen.

- **Direct photobiological conversion**: Various bacteria and algae have been isolated that can produce hydrogen either from organic materials through digestion or directly from water and sunlight through photosynthesis. Both methods rely entirely on renewable resources, such as sunlight, biomass, and biological organisms, to produce hydrogen.

- **Thermal decomposition**: Concentrated solar thermal energy can achieve temperatures exceeding 5,000 degrees Fahrenheit. Under these conditions, water thermally decomposes into hydrogen and oxygen. Separation of the gases before they spontaneously recombine is one problem facing this technology.

Pipeline is the easiest form of hydrogen transmission, although the gas can be compressed or liquefied and transported in tanks as well. Unlike centrally generated electricity, hydrogen can be easily, quickly, and compactly stored and retrieved when needed. Like natural gas, hydrogen can be compressed and held in pressurized storage tanks. Advanced high pressure tanks capable of containing pressures up to 10,000 pounds per square inch have been produced and used in space applications, although most hydrogen is now stored at pressures around the standard of 3,600 pounds per square inch now common in natural gas and other compressed industrial gas storage systems. Alternatively, hydrogen can be liquefied, although the liquefaction temperature—more than 400 degrees Fahrenheit below zero and less than 40 degrees above absolute zero—makes this process difficult. Another set of technologies for storing hydrogen involves reversible adsorption onto the surface of activated carbons. Hydrogen also can be held within the internal structure of metal alloys, called hydrides.

Hydrogen can be stored until needed more easily than electricity. For example, a compressed hydrogen storage system can provide as much energy as a battery meeting the Advanced Battery Consortium's mid-

term commercialization goals, while weighing one-tenth as much and consuming one-third the space.[12] Moreover, when hydrogen storage tanks are depleted, they can be replenished in a small fraction of the time that it takes to recharge batteries.

Thus, a sustainable transportation system can be envisioned that uses renewable resources to produce hydrogen. In this scenario, hydrogen is distributed through pipelines and stored on board electric vehicles. When energy is needed, the hydrogen is fed into an on-board fuel cell generating electricity to propel the vehicle. This electric vehicle energy system can operate independent of centrally generated electricity and batteries, relying totally on the fuel cell for electricity. Alternatively, the two systems can be intertwined in "hybrid" electric vehicle configurations that include fuel cells and batteries. Batteries can be recharged from the grid while the vehicle is parked or they can rely on the on-board fuel cells for the electricity they store. In the latter case, batteries can be used to provide energy during fuel cell warm-up upon starting, assist the fuel cell in meeting peak acceleration energy demands, and capture energy through regenerative braking.[13]

Status of Hydrogen Commercialization

Only in the last few years has hydrogen begun to be taken seriously as a transportation fuel. Much recent activity in the field has focused on fuel cell applications in buses.[14] In 1993, Ballard Power Systems, based in Vancouver, Canada produced the world's first fuel cell bus. Chicago and Vancouver have each purchased three second generation fuel cell buses from Ballard for delivery in 1997. In the early 1990s, DOE sponsored a program to build three fuel cell buses, now undergoing tests in the District of Columbia, Illinois, and California. In 1996, the U.S. Department of Transportation assumed leadership over the second phase of this project. Two more fuel cell buses will be built over the next few years. Fuel cell bus projects are also underway in Italy, Belgium, and Germany.

Company officials have publicly stated Mercedes' belief that fuel cells will be the technology most likely to supplant internal combustion engines in automobiles.

The first modern-day fuel cell concept automobile, the Green Car, was unveiled by Energy Partners, Inc., in Florida in 1991. Most major automotive manufacturers worldwide now have fuel cell development projects and a few have unveiled prototype vehicles. In May 1996, Mercedes showcased its second fuel cell vehicle, a six-passenger van called the NECAR II, at a widely publicized press event in Berlin. (The NECAR I was tested in 1994.) Company officials have publicly stated Mercedes' belief that fuel cells will

---

[12]Hydrogen storage issues are discussed in *Harnessing Hydrogen: The Key to Sustainable Transportation*, chapter V. Specific comparisons between hydrogen and battery storage systems appear on pages 132-142.

[13]Conventional brakes waste the energy released as heat that is generated by the friction of the brake shoes when a vehicle slows down. Regenerative brakes are equipped with electrical generators that capture some of this energy and use it to produce electricity to propel the vehicle.

[14]New leading periodicals that monitor current events in the hydrogen field include the *Hydrogen and Fuel Cell Letter*, published by Peter Hoffman in Rhinecliff, NY; and the *Clean Fuels and Electric Vehicles Report*, published by J.E. Sinor Consultants in Niwot, CO.

be the technology most likely to supplant internal combustion engines in automobiles. In October 1996, Toyota unveiled its first fuel cell demonstration vehicle at a conference in Osaka, Japan. In January 1997, Chrysler exhibited a fuel cell vehicle design at a Detroit auto show.

Hydrogen is being used as a combustion fuel to power vehicles with conventional engines, as well as fuel cell vehicles. Several major automotive manufacturers that use hydrogen to power conventional combustion engine-equipped automobiles include Daimler Benz and BMW in Germany, and Mazda in Japan. Each has built a number of hydrogen-burning prototype vehicles as part of hydrogen programs initiated in the early 1980s. Several hydrogen burning pick-up trucks also operate as part of the two solar hydrogen vehicle test programs in southern California mentioned earlier. Moreover, a hydrogen-powered electric hybrid bus began operating in Augusta, Georgia in September 1996. Two buses in Montreal burn a mixture of natural gas and hydrogen called Hythane.® Hydrogen buses are being tested in demonstration projects in Germany and Belgium, and a hydrogen-powered delivery truck operates in Japan.

According to an International Energy Agency study, significant hydrogen energy programs are underway in at least eleven countries.[15] Throughout the 1980s, Germany conducted the world's largest government-sponsored hydrogen program, involving more than $300 million in total investment. In 1993, Japan eclipsed Germany with an $2.8 billion World Energy Network (WE-NET) program to develop and commercialize a global hydrogen production, distribution and use system. In the United States, the National Hydrogen Program is one of the few programs in DOE's Office of Renewable Energy and Energy Efficiency whose budget grows steadily. As shown in Table 1, annual expenditures for this program have increased from $1.8 in fiscal year 1992 to $15 million in fiscal year 1997.

The Hydrogen Future Act became law in October 1996. The Act mandates that government-sponsored hydrogen research, development, and demonstration project expenditures totaling over $100 million will be conducted over the next five years. Beyond the National Hydrogen Program, annual expenditures on hydrogen of over $20 million are part of the National Fuel Cells in Transportation Program. Hydrogen fuel cells are also being studied as part of the Partnership for a New Generation of Vehicles, initiated by President Clinton in 1993 as a collaboration between the federal government and the major U.S. automotive manufacturers.

Why Pursue Hydrogen as a Renewable Transportation Fuel?

Hydrogen that is manufactured from renewable resources and used in fuel cells can provide sustainable energy to power electric vehicles. The total system, including distribution, refueling and on-board storage of hydrogen may prove superior to batteries recharged with grid power. A hydrogen-powered electric vehicle may offer a market entry for hydrogen and renewable resources in transportation. Attractive transitional applications of hydrogen include use in combustion engine vehicles and production from natural gas. In either case, the environmental and energy policy consequences are significantly less than continued use of oil-derived fuels in conventional combustion engine vehicles.

---

[15] International Energy Agency, *Hydrogen Energy Activities in 11 IEA Countries* (Silver Spring, MD: International Planning Associates, Inc., Dec. 1994).

The logic of pursuing a market entry opportunity for renewables-based hydrogen in transportation is based on the six considerations discussed below. To provide a context for the sustainable hydrogen transportation strategy, comparisons are offered to market entry opportunities in centralized power generation that have received considerable support from renewable energy advocates to date.[16]

1. The Nation's Energy Security Problem is Most Severe in the Transportation Sector

In the 1970s, the nation endured a series of energy crises. The 1973 oil embargo severely disrupted petroleum supplies and substantially raised the price of all fuels. A second oil crisis in 1979 led to further price hikes and sporadic fuel supply shortages. The electrical generation sector reduced oil use and diversified and expanded its use of domestic energy resources. The utility industry successfully weaned itself from its thirst for oil, reducing the fraction of generation fueled by oil from 17% in 1973 to 3% today.[17]

Even assuming a modest 2% annual growth for global oil consumption, the world will consume more oil during the next twenty years than it has throughout history.

Indisputably, adequate reserves of coal exist in the United States to support electrical generation markets; the constraint on coal use always has been its environmental effects, not resource availability. Natural gas supply has performed a dramatic about-face since the shortages of 1979. It now appears that supplies are adequate to meet projected electric generation markets for at least several decades.[18] Combined cycle power generation using natural gas has emerged as a very clean, highly efficient, and low-cost technology. It is currently the least expensive provider of energy for most new capacity additions.

By contrast, the transportation sector remains almost entirely dependent on oil, and the United States' petroleum vulnerability has worsened. Domestic oil production has dropped 24% since 1970 due to depleting low-cost reserves; total oil use, propelled mainly by increased use in transportation, has risen 20%. Imports, which accounted for just 21% of total U.S. oil consumption in 1970, now approach 50%.[19] The bill for imported oil now exceeds $55 billion per year. The United States spends an additional $50 billion annually to maintain a military presence in the Middle East partly to secure the continued flow of oil.

Global oil use is growing. Even assuming a modest 2% annual growth for global oil consumption, half the actual growth rate experienced during the 20th century, the world will consume more oil during the next twenty years than it has consumed throughout history. Moreover, should countries with minimal

---

[16]This paper does not review all the relevant transportation issues or opportunities for renewable resource use. There are other options for sustainable transportation besides hydrogen and grid-charged battery electric vehicles, such as biomass-derived alcohol fuels in combustion engine vehicles. Other renewable energy market entry opportunities besides transportation and centralized power generation exist as well, such as distributed remote and roof-top solar applications.

[17]Edison Electric Institute, *Statistical Yearbook - 1992* (Washington, DC, 1993), 29.

[18]Gas Research Institute, *1993 Edition of the GRI Baseline Projection of the U.S. Energy Supply and Demand to 2010* (Chicago, IL, 1993), 71-84.

[19]*Annual Energy Review 1994*, 139.

automotive infrastructure expand their use of gasoline-burning automobiles, international competition for oil will become intense. In China, for example, there is one car for every 652 people; in the United States, there is one car for every 1.5 people. Viewed another way, the United States has 19 million more vehicles than registered drivers. If China or other developing nations seriously enter the competition for oil, global oil demand would soon far exceed production capacity.[20]

1. Pollution From Transportation Has Created Severe Environmental Problems

The environmental consequences of oil use in conventional automobiles are staggering. Emissions from transportation now account for roughly 50% of all air pollution regulated under the Clean Air Act. Because automotive use is concentrated in cities, the total pollution due to transportation in most urban areas, including toxic air pollutants such as benzene and formaldehyde, exceeds 60%.[21]

Because automotive exhausts generally occur at ground level in populated areas, the human health effects of tailpipe emissions are enormous. Public awareness of the impact of transportation pollution is also high. The emissions of hydrocarbons and nitrogen oxides together are particularly disturbing because their interaction in the atmosphere causes ozone, or smog, which is the most critical air quality issue facing many cities. Particulate emissions, largely from the exhaust of diesel fuel engines, are also especially worrisome because they have been linked to severe respiratory problems, including premature deaths.[22]

Fortunately, tailpipe emissions of criteria pollutants from the average automobile have been reduced since 1968 by more than 60% as a result of tighter standards set in the Clean Air Act. Unfortunately, lower emissions per mile have been offset largely by increased numbers of vehicles and driving miles. Further reductions in per vehicle automobile emissions undoubtedly will occur as new fuel reformulations, engine controls, and tailpipe pollution control equipment are introduced. However, using these strategies to improve ambient air quality in densely populated areas may be less effective than using emerging alternative fuels and renewables-based propulsion systems.

Environmental problems due to transportation are on the same order of magnitude as those problems resulting from power generation. Together, these two sectors account for most of the air pollution regulated under the Clean Air Act. Emissions of nitrogen oxides, hydrocarbons, fine particulate matter, and carbon monoxide from electricity generation are now below those stemming from transportation. Electrical

---

[20]For example, if China were to increase its per capita consumption of oil to an amount equivalent to the per capita consumption of Mexico, global oil production would have to increase by 70%. Energy Futures, Inc. calculations using data from the American Automobile Manufacturers Association, *World Motor Vehicle Data: 1996 Edition (*Detroit, MI, 1996).

[21]U.S. Environmental Protection Agency, *National Air Quality and Emissions Trends Report, 1995* (Washington, DC, Oct. 1996). Although detailed emission inventories within the transportation category are lacking, cars, buses, and trucks probably account for between 65% and 85% of total transportation-related air pollution. Because these vehicular emissions occur at ground level and mostly in populated areas, their public health impact likely exceeds their percentage contribution.

[22]For further information, see Curtis Moore, *Dying Needlessly: Sickness and Death Due to Energy-Related Air Pollution*, REPP Issue Brief 6, February 1997, available from REPP at (301) 405-4550 or on the Internet at http://solstice.crest.org/renewables/repp/.

generation surpasses transportation slightly for emissions of carbon dioxide but remains by far the largest source of sulfur dioxide, accounting for 72% of the nation's total.[23]

1. The Economics of Renewable Resource Use in Transportation Appear at Their Most Favorable

The cost of gasoline at the pump, like electricity, has dropped in real terms over the past twenty years. The national average price of unleaded gasoline, for example, was 25% less in 1994 than in 1976.[24] Gas prices are beginning to increase, however, as costs of producing cleaner reformulated gasoline are added to the pump price.[25] More importantly, perhaps, Americans are much more aware of factors affecting the cost of a gallon of gasoline than of those affecting the cost of a kilowatt hour of electricity. For example, film clips about expensive U.S. military actions in the Middle East frequently appear on television news. Events like these remind people that the true costs of oil dependence in transportation greatly exceed the pump price of gasoline.

Renewables-based hydrogen could compete head-to-head with gasoline in terms of fuel cost per mile driven because electric propulsion systems are up to three times more efficient than internal combustion engine systems.

On the other hand, the price of hydrogen-based transportation options, although still higher than conventional fuels and technologies, is dropping. Furthermore, the use of hydrogen in fuel cell vehicles offers a key economic advantage over gasoline used in conventional vehicles. In transportation, hydrogen competes head-to-head with gasoline in terms of fuel cost per mile driven. Because electric propulsion systems are between 1.5 and 3.0 times more efficient than internal combustion engine systems, less fuel is needed per mile driven. Therefore, hydrogen can cost more than gasoline, yet still be the cheaper fuel per mile of driving. This leverage factor greatly reduces the economic barrier facing renewable resource use in transportation. In fact, the cost of hydrogen produced today from biomass or wind farms is competitive with the cost of gasoline on a per mile driven basis. Hydrogen produced from natural gas and used in a fuel cell vehicle is considerably cheaper than gasoline per mile driven.

Future gains in gasoline-burning internal combustion engine efficiency may erode this leverage, but renewables currently have a sizable advantage in transportation. In contrast, they are at a disadvantage in centralized electrical generation, where more expensive renewable-based electricity must compete one-to-one, kilowatt-hour for kilowatt-hour, with power generated from cheaper fossil fuels.

2. Public Policies and Programs to Promote Alternative Transportation Fuels are Expanding

---

[23] U.S. Environmental Protection Agency, *National Air Quality Emissions Trends Report, 1994*, Washington, DC, 1995.

[24] *Annual Energy Review 1994*, 181.

[25] Use of reformulated gasoline and cleaner grades of diesel will not be sufficient to restore urban air quality and they do nothing to reduce oil dependence. See J. Cannon, *Reformulated Gasoline: Cleaner Air on the Road to Nowhere* (New York: INFORM, Inc., 1994).

A serious effort to begin the transition to a post-petroleum age has been underway in the United States since the late 1980s. The Clean Air Act of 1990 and the Energy Policy Act of 1992 both contain mandates and incentives for alternative transportation fuel use in specific automotive fleets. Several of these fleets are required to use an increasing amount of alternative fuels beginning in 1997. Furthermore, more than thirty state governments have acted on their own to establish alternative transportation fuel use mandates and incentives that are often more vigorous than federal efforts. California and Massachusetts, for example, have adopted requirements for the development of demonstration vehicle programs, followed by the introduction of zero-emission vehicles early in the next decade.

Due to these efforts, a substantial alternative transportation fuel industry has formed in the 1990s. Use of natural gas, propane, and alcohol fuels in transportation, although still minuscule compared to oil use, has increased dramatically, paving the way for the zero-emission electric vehicle technologies now entering the marketplace. Table 1 shows the current status of U.S. transportation fuel use.[26]

The emergence of a nascent alternative transportation fuels industry in the United States has recently been threatened by a counter movement from the major auto and oil companies which favor oil-derived fuels and conventional pollution abatement strategies based on tailpipe emission control technology. Moreover, some government programs are under attack by opponents of alternative fuel mandates, who view them as inappropriate market intervention. Insufficient funding hampers several government fleet conversion projects and concern over fiscal impacts undermines support for some alternative fuel use financial incentives. Nonetheless, innovation in transportation is far more vibrant today than a decade ago, in contrast to the erosion of renewable energy opportunities in the electricity industry during the same period due to industry restructuring.

3. Hydrogen Transportation Can Benefit From Synergy With Emerging Natural Gas and Electric Vehicle Technologies

Until the technologies for hydrogen production from renewable resources becomes widespread, hydrogen produced from natural gas is available as a commercially-established, clean, and low-cost method of hydrogen production. Moreover, there is an advantageous synergy between the natural gas vehicle technology now being commercialized and the technology that will be needed to support a hydrogen-based transportation system. Use of natural gas vehicles helps pave the way for hydrogen by transforming the transportation system from one reliant on liquid fuels to one equipped for gaseous fuels. This fundamental change is being undertaken by an industry with far greater financial resources than those of hydrogen supporters. An extensive fuel delivery infrastructure is already in place and growing. If natural gas vehicles become common, switching from natural gas to hydrogen in the future will involve, for many components, incremental, rather than fundamental, changes.[27]

---

[26]Estimates by Energy Futures, Inc. from data in Energy Information Administration, *Alternatives to Traditional Transportation Fuels: 1995* (Washington, DC, 1996).

[27]Natural gas vehicle technology and its synergy with hydrogen vehicles are discussed in J. Cannon, *Paving the Way to Natural Gas Vehicles (*New York: Inform, Inc., 1993).

During the transition, use of natural gas vehicles would provide important environmental and energy security benefits compared to continued reliance on oil. Several natural gas vehicles have been certified to meet the California ultra-low emission vehicle standard. To date, no gasoline-powered vehicles have been certified to meet the ultra-low or proposed equivalent zero-emission standards. Fuel cycle analyses performed by the International Energy Agency and others conclude that total emissions from natural gas vehicles, including natural gas leaks from pipelines, are less than emissions from the petroleum fuel cycle.[28]

Synergy also exists between today's electric vehicles, which are powered largely by electricity stored in batteries, and hydrogen fuel cell electric vehicles of the future. A kilowatt-hour of electricity generated by a fuel cell is identical to a kilowatt-hour drawn from a battery. Hence, most of the electric vehicle system that is designed to serve battery-equipped vehicles—including the motor, controllers, and regenerative brakes—will apply directly to fuel cell vehicles.

The natural gas and electric battery vehicle industries hardly view their roles as limited to promoting transitional technologies; ultimately, hydrogen will have to compete on its own to win consumer acceptance. Development of enabling technologies and compatible infrastructures where none now exist will speed the transition to hydrogen.

4. Consumer Involvement and Choice is High in Transportation

A consumer who knows that his local powerplant uses renewable resources to generate some of its electricity has no way to discern whether the electricity he uses is powered by renewable or fossil resources. Moreover, because electricity has been a regulated industry for the past century with monopoly status within service franchises, consumers have little experience making electricity purchase selections. The electricity industry is rapidly changing and consumer choice is becoming a reality. Consumers will have to learn what selection criteria exist in this new area of consumerism, what their opinions are about those selections, and how to make those preferences known through purchase decisions. Education is critical if consumers are to make informed decisions about their future electricity options. However, such education is not as critical in transportation, where a larger, educated and experienced consumer base already exists.

Consumers are bombarded daily with advertisements aimed at influencing automobile purchase decisions; they have a great deal of experience making these selections in the face of intense pressure. There are more than two hundred automobile models for sale in 1997, and purchasing an automobile is one of the most costly and deliberate decisions most consumers make. The perceived importance of the automobile has reached stratospheric levels in American culture, not only as a transportation medium, but as a reflection of psychologically complex consumer preferences about unrelated characteristics, such as color, comfort, and horsepower far exceeding the requirements for legally permissible driving.

A transportation market entry approach for advanced technologies based on renewable energy, therefore, may find a receptive audience among some consumers. They may appeal, for example, to "innovators" and "early adopters" who wish to be among the first to own and test new technologies. They may appeal to environmentally-concerned, "green" consumers who wish to reduce their personal responsibility for creating

---

[28]International Energy Agency, *Cars and Climate Change (*Paris, France, 1993).

tailpipe pollution. Such consumers can directly verify that their actions make a difference because their vehicles have no tailpipes, yet alone tailpipe emissions. Because of the risks involved in purchasing advanced technologies for such an expensive product, these early market participants may be limited to the risk averse; however, the initial buyers may prove crucial to generating wider consumer acceptance.

RECOMMENDATIONS

Transportation is where society's environmental, energy, and economic problems are most severe, where the rationales for changing the status quo are most compelling, and where opportunities to develop consumer support are strongest.

The ultimate merging of the two energy revolutions growth—in electricity production and increased transportation mobility through the automobile—appears inevitable in the next century as automobiles are electrified and fossil fuels yield to renewable resources. When this merging occurs, a sustainable energy economy will be possible. Efforts to increase the use of renewable resources in both markets are critically important. Hydrogen may play an important role in the merger of electricity and transportation by providing an energy carrier for renewable resources that is well suited for electrical generation in transportation applications.

The movements toward alternative transportation fuels in general and toward hydrogen vehicles in particular face huge obstacles to success, not the least of which is intense opposition from the automotive and oil industries. Using renewable resources in centralized power generation is in many ways easier than using renewable resources to power hydrogen fuel cell vehicles, but transportation is the energy sector now under siege. Transportation is where society's environmental, energy, and economic problems are most severe, where the rationales for changing the status quo are most compelling, and where opportunities to develop consumer support are strongest.

A market entry approach based on the ability of renewable resources to supply hydrogen energy in transportation may be an important addition to efforts to encourage renewable resource use in the electrical generation mix. A market entry strategy for hydrogen in transportation could include the following six elements:

1. ***Build widespread support around the tremendous adverse environmental, energy, and economic consequences of remaining dependent on oil and combustion engine automobiles.***

The two greatest problems facing advocates for change in transportation are, first, the lack of public understanding of the broad range of consequences associated with continued reliance on oil and conventional vehicles in transportation; and, second, the lack of confidence in the exciting possibilities presented by the transition to alternative vehicles. Public education is probably the single most important factor in accelerating the sustainable transportation era. One place to start is exposing problems in the status quo.

2. Develop market pull from consumers through public demonstrations of alternative transportation fuels and zero-emission vehicles that can help expand the demand for these vehicles by innovators, early adopters, and green consumerism.

Highly visible demonstrations, such as urban bus projects, and well-publicized programs, such as the EV1 commercialization, are critical to developing public support for alternative vehicles. This second step, therefore, is needed to illustrate the advantages of sustainable transportation.

3. ***Encourage government efforts to promote use of alternative transportation fuels.***

Government programs to address oil dependence and automotive air pollution must be supported, strengthened and sustained. Hydrogen and electric vehicles are not yet major players in most alternative transportation fuel use programs implemented in response to the 1990 Clean Air Act and the 1992 Energy Policy Act, or under most state government initiatives. Sustainable transportation advocates need to have a more forceful presence in these programs.

4. ***Support government and private sector research, development, and demonstration of sustainable transportation systems using renewable resources to produce hydrogen that powers fuel cell vehicles.***

Although the budget for the National Hydrogen Program has grown this decade, it still remains barely 0.2 of 1% of DOE's budget, a level that is totally inadequate to achieve its goals. (See Table 2.) Improvements are needed before many components of renewable resource-based hydrogen fuel cell systems are ready to enter commercial production. Research is particularly needed on direct hydrogen production from renewable resources, techniques to increase the power density of fuel cells, and fuel storage approaches with lower weight and volume requirements.

5. ***Promote the two key transition technologies that hydrogen needs to develop automotive systems for use in electric vehicles powered by fuel cells.***

Two transitional technologies—natural gas vehicles to shift the fueling infrastructure from liquid to gaseous fuels and electric battery vehicles—are critical to disrupting the status quo, triggering change, and establishing some of the necessary components of sustainable transportation systems. Natural gas, electric battery, and fuel cell-powered vehicles are all part of the movement away from oil and toward sustainable transportation. Unity rather than competition among proponents of these fuels and technologies is needed if attempts to challenge the awesome inertia of the oil-based transportation system can ever hope to succeed.

6. ***Advocate including sustainable transportation fuels and propulsion technologies among other strategies to improve the nation's transportation system.***

Perhaps the most discouraging aspect of the current movement toward sustainable transportation (and fortunately the easiest to remedy) is a lack of solidarity among advocates of different approaches to achieve this goal. Transportation is a multi-dimensional problem that defies single-action solutions. Zero-pollution vehicles, for example, will not solve our transportation problems without a reduction in vehicle miles

traveled and travel will not be reduced without innovative land use planning. There is skepticism and occasionally even hostility among advocates focusing on different components of the sustainable transportation equation. Efforts that bring together the entire transportation reform community are critical to developing this solidarity.

Many activities are underway that address one or more of these elements. The challenge is to expand and coordinate them. A unified and widely supported strategy exists to promote renewable resource use in centralized power generation, but does not in transportation. Now is the time for renewable energy advocates to plan carefully to make sustainable transportation possible in the 21st century.

TABLE 1 FUEL USE IN U.S. TRANSPORTATION 1997		
Fuel Type	**Fuel Use (millions of equivalent gallons)**	**Number of Vehicles**
Gasoline	120,100	155,000,000
Diesel	27,800	35,000,000
Propane	245	273,000
Natural Gas	86	82,700
Methanol (M85)	4	19,800
Ethanol (E85) & Biofuels	2	6,200
Battery Electrics	1	3,900
Hydrogen	<1	<20

TABLE 2 NATIONAL HYDROGEN PROGRAM EXPENDITURES	
Fiscal Year	**Amount (millions $)**
1992	$ 1.4
1993	$ 3.8
1994	$ 9.5
1995	$ 10.0
1996	$ 14.5
1997	$ 15.0