A sustainable hydrogen energy industry — an energy system based upon the extensive use of hydrogen as an energy storage and transportation medium — must be established if an environmentally and economically sustainable world is to be left to our children and grandchildren. Few doubt that the hydrogen energy industry will eventually evolve. Many debate the timing of such a development. Only by defining the nature of a future hydrogen energy system, by identifying the path to such a system, and by actively taking the first steps along that path will we, as a world society, achieve that goal in time to avoid serious environmental and economic disruptions.

The National Hydrogen Association, in conjunction with the U.S. Department of Energy, is embarking upon the process of defining the path and beginning the journey. The NHA believes that this journey will only be successful by working together in an industry/government partnership. Neither group can succeed alone. Both have unique strengths and weaknesses.

Industry has the expertise and financial resources to bring new products to the marketplace. But industry must respect the bottom line and the demands of its stockholders to provide short-term return on investment. Industry cannot finance long-term societal goals such as clean air and reduced dependence on foreign oil.

Conversely, governments are notoriously sluggish and inefficient whenever they attempt to force new technology on the marketplace; witness the synthetic fuels fiasco. But governments have the sole charter to "protect the commons" — in this case, the environment — from the excesses of individuals or corporations pursuing their own economic self-interest. Government alone has the long-term staying power and the mission, acting on behalf of all citizens collectively, to develop and promote new technology and new policies that will achieve societal objectives. Working together, government can provide the seed money and regulatory environment to start the process, and industry can provide the marketplace savvy and the large capital investment, once the hydrogen technology development comes within industrial planning horizon time scales.

## Objectives of the Hydrogen Commercialization Plan

This hydrogen commercialization plan is one major tool needed to implement the National Hydrogen Association mission statement:

> ...to foster the development of technologies and their utilization in industrial and commercial applications and promote the transition role of hydrogen in the energy field.

The Hydrogen Commercialization Plan is a living document to be revised and expanded over the coming years as more and better information becomes available about new technologies and the growing market for hydrogen energy systems.

The primary objective of the plan is to obtain commitments from both industry and government to begin implementing the hydrogen energy industry. Such joint commitment will require an economically and technically feasible road map on how to get from here to there. Industry must be convinced that it can eventually make a return on investments in hydrogen technology. Government must be convinced that its investments will leverage larger societal benefits in the form of reduced health costs, reduced oil imports, and improved international competitiveness over time. In short, the hydrogen commercialization plan must point to a credible benefit/cost ratio for all participants.

It is our intention that this plan will be used to:

- identify unique niche market opportunities where hydrogen is economical now, or nearly so, with growth potential toward longer-term goals.

- convince appropriate companies, both members and nonmembers of the NHA, to make investments in hydrogen development, demonstration, and commercialization projects, with industry paying an increasing share of the cost as each technology approaches market viability.

- convince government decision makers to provide steadily increasing support for hydrogen and fuel cell development programs in the near-term, with the realization that these technologies will eventually become economically viable on a broad scale without any government support.

- help guide hydrogen energy investment choices by government agencies in the industrialized world, including choices by the U.S. Department of Energy.

- help convince other key players — such as state and local officials, building inspectors, the insurance industry, the investment industry, and the public at large — that the hydrogen energy industry is safe, economical, and sustainable.

- encourage other companies and organizations to join the NHA.

This commercialization plan begins by identifying the most likely early markets for hydrogen as an energy carrier, and sets realistic near-term and mid-term goals for selected market penetration. The plan outlines the incentives (see Appendix I) and the major barriers to achieving those goals, and recommends activities to capitalize on the incentives and overcome the market barriers.

Opportunities for early market entry exist near hydrogen plants and by-product hydrogen sources. Infrastructure growth potential is most favorable where natural gas or off-peak electricity prices are low. The locations of existing renewable energy facilities point the way toward the future.

The plan identifies specific action items to overcome each major barrier, with primary emphasis on near- and mid-term results, with the understanding that the transition from fossil-based fuels to sustainable, renewable hydrogen is the most difficult task. Taken together, these actions will provide a realistic transition path toward the Hydrogen energy industry.

## The Market Sectors

In a truly sustainable world, all energy will be carried by either hydrogen or electricity; carbon-based fuels will not be acceptable. Hydrogen will become especially important in those economic sectors in which storage or transportation of energy is required and electricity is less effective or more costly as an energy carrier.

### Transportation

A municipal subway system may be powered economically with electricity from a fixed source delivered to the trains by wires or rails. But a personal automobile intended for a trip from Seattle, Washington, to Los Angeles, California, requires that a fuel be stored onboard the vehicle. Hydrogen will be that fuel in a sustainable world.

Other terrestrial transportation requirements will also be logical markets for hydrogen-fueled vehicles. These markets include trucks, buses, and, in some locations, trains. All water and air transportation activities will be fueled by hydrogen, since electricity from fixed sites is impractical and no foreseeable battery technology will suffice.

### Fixed Power Plants

Hydrogen will also play a role in the generation of electricity at fixed power plants. In addition to the present use of hydrogen as a coolant for electrical turbines, hydrogen will become a fuel. In those remote locations without an electrical grid, electricity from solar, wind, tidal, and other renewable sources will be used increasingly in a sustainable world. These sources of electricity are often intermittent and require a storage component. Even relatively steady sources of electricity, such as hydropower, may benefit economically from an energy storage system to meet peak power requirements. Hydrogen produced from off-peak or surplus power can be used to store energy for delivery — as electricity — when needed.

Ultimately, hydrogen will be available to each residence and business through a pipeline infrastructure, analogous to the present natural gas pipeline network. Hydrogen will be used to supply electricity to each home and business by locally sited fuel cells, which provide the electricity as well as space heating, with no air or water pollution, in a quiet unobtrusive manner compatible with our daily environment. Such a distributed generation system may eliminate the need for large, central power plants and provide electric utilities with increased flexibility in the design of their systems. Indeed, natural gas-powered stationary fuel cells are already sold as environmentally clean distributed co-generation power systems, serving as a test bed and precursor to future hydrogen-powered co-generation systems.

## Industrial Applications

While the transportation and fixed-site electricity markets are the most challenging and the highest profile areas for the growth of a hydrogen energy industry, many present and new industrial applications for hydrogen also will develop. Most industrial applications can be effectively served by electricity. Exceptions are those industries that produce low-cost hydrogen as by-products or those that already use hydrogen for other purposes. These industries may provide the initial sites for acceptance of transportation and fixed-site electricity generation using hydrogen.

While industrial applications must and will be pursued, it is important that these not distract from efforts to achieve the broader public use of hydrogen in transportation and fixed-site electricity generation, which is the primary focus of this NHA commercialization plan.

## Hydrogen Commercialization Goals

For planning purposes, the National Hydrogen Association has set market penetration goals in the two primary market sectors identified above. These goals should be considered preliminary, and will be modified in response to new information, including new technological developments and further hydrogen systems analyses. While these goals may change, it is important to establish commonly shared benchmarks now, so that all participants can focus and coordinate their efforts.

Achieving these goals will require significant contributions and continued successful technological developments in areas outside the scope of the U.S. Department of Energy's Hydrogen Energy Program, which is part of the Office of Utility Technology under the Assistant Secretary for Energy Efficiency and Renewable Energy. Meeting the transportation goals listed below will require the successful development of either hybrid electric vehicles with hydrogen-fueled internal combustion engines or direct hydrogen fuel cell vehicles.[1] In the United States, the Office of Transportation Technology, separate from the Hydrogen Energy Program manages both the hybrid and the fuel cell for transportation programs.[2]

A viable hydrogen-fueled vehicle also will require improvements in other electric vehicle components such as electric motors, controllers, and peak power augmentation devices. And, most importantly, the transportation goals will only succeed if public acceptance and demand for value-added products allows the automobile industry to put hydrogen-fueled vehicles into mass production. Hence, the goals listed below are joint industry/government goals. The NHA action items listed in subsequent sections of this plan, however, will address primarily those areas where NHA and its members can make the greatest impact, such as in hydrogen fuel supply. We assume that other players will buy into these broader goals and jointly pursue these common goals.

Similarly the fixed power plant goals assume continued development of stationary fuel cells, hydrogen storage, and fuel cell/grid interface hardware. And our common goal of renewable hydrogen energy depends strongly on reduced costs for photovoltaics, wind energy, solar thermal generators, and biomass energy farms. We assume here, however, that the limited funding available to the Hydrogen Energy Program could have very little impact on reducing the costs of PV, for example. Diverting even a portion of a US$29 million annual hydrogen program to assist a US$78 million PV program or a US$110 million solar energy program would not be appropriate (FY2001 Budget Numbers). This plan, therefore, assumes that PV and other solar options will develop on their own time-scale, and the hydrogen program should concentrate strictly on hydrogen-related components of remote power systems, including electrolyzers, stationary hydrogen storage, and fuel cell systems.  Renewable hydrogen energy will enter the marketplace when and where it is cost-effective compared to the other local forms of energy.

With these caveats, the National Hydrogen Association recommends the following goals for the joint industry/government hydrogen energy program.

## Transportation Goals

### Hydrogen Vehicle Demonstration Goal

By 2003, establish at least three additional hydrogen vehicle demonstration projects, including local hydrogen production by small-scale steam methane reforming or small-scale electrolysis, and dispensing to service at least 10 hydrogen-powered vehicles each.  Vehicles may store gaseous or liquid hydrogen, and the fuel might include mixtures of hydrogen and natural gas.  At least one demonstration project will produce hydrogen from a renewable resource (solar, wind, or biomass) or from municipal solid waste (MSW).

### Hydrogen Bus Goals

1. By 2004, operate at least 100 hydrogen-powered buses on regularly scheduled routes.  Cost goals include hydrogen-fueled ICE hybrid or fuel cell power train systems at less than US$533/kW and dispensed hydrogen costing less than US$6.27/kg (US$14.82/1,000 SCF) for bus refueling.[3]

2. By 2010, 50 percent of all new buses shall be powered by hydrogen.  Cost goals shall include hydrogen-fueled ICE hybrid power train or fuel cell production costs less than US$85/kW and delivered hydrogen costs of less than US$4.70/kg (US$11.12/1,000 SCF), made from natural gas at US$6.27/MBtu (US$6.35/1,000 SCF) or from renewable resources, including municipal solid waste.

### Hydrogen-Fueled Passenger Vehicle Goals

1. By 2010, produce enough hydrogen to supply 50 percent of all new vehicles sold under the California Zero-Emission Vehicle (ZEV) program (including other opt-in states), on the assumption that half of these vehicles will be hydrogen-fueled.[4]

2. By 2015, produce enough hydrogen to supply 25 percent of *all* new passenger vehicles.  Cost goals include hydrogen-fueled ICE hybrid power train or vehicle fuel cell systems at less than US$37/kW and delivered hydrogen at less than US$3.92/kg (US$9.27/1000 SCF) from natural gas at US$6.27/GJ (US$6.35/1,000 SCF).

## Fixed Power Plant Goals

### Grid-Connected Goals

1.By 2002, install at least 50 MW (cumulative) of hydrogen-powered[5] fuel cell electricity for distributed, grid-connected power in the world.

2.By 2015, 10 percent of all new electrical generation capacity shall be from hydrogen-powered fuel cell [cogeneration] systems. [Alternative:  By 2005, hydrogen-powered fuel cells will supply 50 percent of new market "High Quality Power" applications, replacing the need for onsite "emergency" generators and UPS systems.]

### Remote Power Goals

1.By 2005, establish two or more remote/ECO village power demonstration projects using intermittent renewable energy sources and hydrogen to store energy.  Cost goal for the energy derived from hydrogen storage shall be less than the cost of battery storage for storage periods longer than four days.

2.By 2015, install at least five megawatts of remote renewable power systems with hydrogen storage.  Cost goal for hydrogen energy shall be less than the cost of battery storage for storage periods longer than two days.  [Should remote power systems have higher MW goal than grid-connected, since remote power can afford higher initial costs and may be a faster growing market in the developing world?]

## Market Incentives and Barriers

To accomplish these goals, we must capitalize on the incentives for hydrogen energy use and overcome the barriers to its use.

### Hydrogen Incentives

Hydrogen has three main advantages relative to existing hydrocarbon fuels:

- No local air pollution [volatile organic compounds (VOC), carbon monoxide (CO), oxides of nitrogen ($NO_x$), and particulates under 10 microns (PM-10)];
- Reduced oil consumption; and
- No greenhouse gas emissions (during use).

Electricity also has these same three attributes, so the main incentive for using hydrogen over electricity occurs under two circumstances: when storage is important, such as in transportation or remote village applications, or when hydrogen can be made at lower cost than electricity, such as from biomass or municipal solid waste gasification. The key to any successful hydrogen plan, therefore, is to exploit these advantages of hydrogen, particularly in those market segments that require energy storage or energy for transportation.

### Hydrogen Barriers

Analyzing the barriers to hydrogen market entry can provide valuable insight into the most effective use of the NHA, industry, DOE, and other international resources to help jump-start the hydrogen energy industry. By honestly identifying and analyzing the major roadblocks as seen by others, we can work to overcome the barriers.

Market barriers may be different for various participants in the journey toward the hydrogen energy industry. For example, car owners, vehicle manufacturers, hydrogen gas producers, and government officials may have different perspectives and see market penetration differently. Consumers might regard safety as the most important barrier, for example, while gas producers have learned to handle hydrogen safely and may consider the lack of hydrogen vehicles as the major barrier to increased use of hydrogen as an energy vector. Table 1 includes our judgment of how four major segments of society critical to the implementation of the hydrogen energy industry might perceive hydrogen market barriers.

## Table 1. Potential Hydrogen Barriers for the Transportation Market

| | |
|---|---|
| Car Owner Barriers | Safety/Confidence |
| | Lack of Pervasive Hydrogen Fueling Options |
| | Cost |
| Vehicle Industry Barriers | Cost |
| | Lack of Fueling Infrastructure |
| | Onboard Hydrogen Storage |
| | Return on Investment (compared to conventional vehicle investments) |
| | Large Investment Required |
| | Lack of Hydrogen Codes and Standards |
| | Safety |
| Hydrogen Gas Industry Barriers | Lack of Hydrogen Vehicles |
| | Difficulty Obtaining Insurance |
| | Return on Investment (compared to other gas industry investments) |
| | Large Investment |
| | Geographically Dispersed Investments |
| | Long Payoff Time (dependent on vehicle penetration) |
| | Local Fire Marshal (regulations, codes, and standards for fueling stations) |
| | Safety |
| Government Barriers | Minimal Political Awareness, let alone Support |
| | Budget Constraints |
| | Lack of Consensus to Reduce Greenhouse Gases and Move toward a Sustainable Energy Economy |

For the transportation sector, considering all four interest groups summarized in Table 1, the most challenging barrier at this time may be the lack of a hydrogen infrastructure. U.S. automobile companies, thanks to the cost-shared DOE fuel cell vehicle programs, are gaining confidence in the technology of PEM fuel cell powered passenger vehicles. However, they are deterred by the lack of a hydrogen-fueling infrastructure. General Motors and Daimler-Benz have announced their intention to use methanol in their early fuel cell vehicle designs.[6] The Chrysler and Ford fuel cell vehicle cost-shared contracts with DOE originally specified gaseous hydrogen onboard storage, but now Chrysler is considering gasoline with an onboard fuel processor to avoid any new fuel infrastructure development, leaving Ford as the only major automobile manufacturer actively evaluating the direct hydrogen approach in the United States. In addition to Daimler-Benz, BMW has a long history developing liquid hydrogen onboard storage for use in conventional ICE vehicles, and they have recently announced plans for a passenger-size fuel cell vehicle using liquid hydrogen. Toyota has introduced a fuel cell vehicle and Mazda is working on a hydrogen rotary engine.

The near-term choice of onboard fuel (hydrogen versus liquid hydrocarbons such as gasoline or alcohols) will be determined by the technical feasibility, the global climate change implications, and the cost of mass-producing onboard partial-oxidation fuel processing systems or onboard methanol steam reformers, compared to the cost of providing a geographically distributed hydrogen-fueling infrastructure. But even if gasoline or methanol become the initial fuel of choice for hybrid electric or fuel cell vehicles, society will eventually have to make the transition to hydrogen, since the world must eventually develop sustainable energy systems which don't use carbon-based fuels.[7]

The primary challenge for the NHA and its members, then, is to develop a cost-effective, geographically dispersed, hydrogen-fueling infrastructure. This infrastructure will undoubtedly be based on fossil fuels initially, but the hydrogen must eventually be supplied by renewable resources as they become cost-competitive in the decades ahead. Developing a credible plan for such an infrastructure would provide the automobile industry the confidence it needs to move more quickly to hydrogen-fueled passenger vehicles.

To summarize, the key barriers to market penetration in the transportation sector may be:

- The hydrogen infrastructure/hydrogen vehicle "chicken and egg" problem (gas producers will be reluctant to install hydrogen-dispensing stations until hydrogen vehicles are on the road, and the automobile industry will be hesitant to build vehicles until there are many refueling stations);
- Safety or perceptions of hydrogen risk;
- Perceived difficulty of onboard hydrogen storage;
- High initial cost;
- Large investment requirements;

- Uncertain return on investment;
- Difficulty obtaining insurance; and
- Lack of codes and standards or accepted common practices.

The market barriers for grid-connected stationary power production appear to be less than for those for transportation applications. For example, the first three transportation barriers listed above will be reduced or eliminated for a stationary hydrogen power plant. Safety concerns will be lessened since the power plant will be at a fixed site and initially will be installed and operated either by a utility or by a commercial customer with skilled maintenance workers. This is a much lesser risk compared to installing and operating a hydrogen storage system onboard a private automobile.

There will be no "chicken and egg" dilemma with respect to hardware production since each stationary system is produced and sold by a single company.[8] There is no need for cooperation between two different industries to make joint investments in manufacturing equipment, although marketing these systems in some locations brings the natural gas industry into conflict with the electric utility industry. And there is nothing equivalent to the onboard storage barrier in the stationary market; natural gas is consumed as needed to produce hydrogen.

Furthermore, the cost barrier for fuel cell systems may be less difficult — by as much as a factor of 10 — for stationary utility systems than for mobile fuel cell systems (e.g., US$533/kW versus US$53/kW). This is the case even though stationary fuel cells must operate uninterrupted around-the-clock for at least five, if not ten, years (45,000- to 90,000-hour life), compared to an automotive fuel cell that might only need to operate one or two hours per day for ten years (3,000- to 5,000-hour life). Also, the automotive fuel cell is rated by peak power that is rarely used, while the stationary fuel cell normally operates near its rated capacity a majority of the time.

Thus, a vehicle fuel cell costing US$53 per peak kilowatt might have an effective cost of US$373 per average kilowatt produced. On the other hand, stationary fuel cells operate in a much more controlled environment than mobile fuel cells, with steady-state operation and little shock and vibration, reducing cost drivers. In short, the stationary fuel cell system is significantly different from the mobile fuel cell system.

But introducing stationary fuel cells may not contribute significantly to societal objectives of reduced oil imports, reduced urban air pollution, and reduced greenhouse gas emissions. Displacing coal, natural gas turbine, or nuclear-powered electricity with natural gas-powered fuel cell electricity will do nothing to cut oil imports. Stationary fuel cell systems will only reduce urban air pollution in those areas where they displace electrical generators that are located within the urban air shed. Otherwise, the existing fossil fuel plant VOC and $NO_x$ emissions from plants outside the urban areas do not contribute to photochemical ozone formation in the local atmosphere. Stationary natural gas-powered fuel cells will reduce greenhouse emissions by displacing fossil fuel-based electricity, but natural gas-powered gas turbines provide almost the same advantage.[9] We conclude that the transportation market, although more difficult to penetrate, should remain the primary initial target of the hydrogen commercialization plan.

Remote power applications may have some unique barriers. Since the primary market may be outside the industrialized countries, financing may be a roadblock in many developing countries. Maintenance of the relatively complex electrolyzer/hydrogen storage/fuel cell/inverter system may be difficult in remote locations compared to the alternative: storage batteries. Many manufacturers of remote renewable power systems may be unaware of or uncomfortable with a hydrogen storage system technology compared to the conventional battery energy storage, or they may be unaware of the economic advantages of energy storage for their customers.

On balance, however, the barriers to the stationary fuel cell market appear to be less daunting than the challenges faced by the hydrogen transportation market. But the societal rewards for penetrating the transportation market are also substantially greater. Penetration of the utility market with stationary fuel cells will benefit only one of the three major societal objectives mentioned above: replacing coal-generated electricity with natural gas/hydrogen/fuel cell-generated electricity will reduce greenhouse gas emissions.

## The Plan's Approach to Overcoming Market Barriers

A successful hydrogen development program must address and eventually overcome each of these barriers, while exploiting the incentives to use hydrogen. The NHA hydrogen commercialization plan seeks to address each of the market entry barriers, as discussed in the following sections. We begin with the transportation market, since the barriers appear to be higher.

### Overcoming Transportation Market Barriers

**Overcoming the Chicken and Egg Dilemma.** The plan emphasizes four elements that will assist both hydrogen gas suppliers and hydrogen vehicle manufacturers to overcome their reluctance to enter the market. We can ease the chicken-and-egg dilemma with a combination of:

- using existing excess by-product hydrogen or excess merchant hydrogen capacity, either liquid or gaseous[10];
- developing small-scale hydrogen generators, using either electrolysis or fossil fuel processors[11];
- starting hydrogen vehicle sales with centrally refueled fleet applications, including buses and both government and private passenger vehicle fleets; and
- establishing hydrogen corridors to connect islands of hydrogen fueling stations constructed earlier for the hydrogen-fueled vehicle fleets.

In the very early days of hydrogen vehicle market penetration, there will be too little demand to justify building new conventional hydrogen production capacity. Gas suppliers generally build very large steam methane reformers to reduce the cost of hydrogen. For example, a typical 30 metric ton per day plant would provide enough hydrogen for a fleet of about 40,000 hybrid-ICE or 60,000 fuel cell passenger vehicles. It may take many years before there are 40,000 to 60,000 hydrogen-fueled vehicles within range of a given gaseous hydrogen plant.

One solution is to find centrally fueled vehicle fleets that are located near existing hydrogen plants or chemical plants with excess hydrogen capacity. The hydrogen gas merchants might install refueling stations on their property to sell excess hydrogen and improve their capital recovery and profitability. In some cases, industrial hydrogen gas users that are already served by hydrogen pipelines might be induced to fuel their company vehicles with this readily available on-site hydrogen.

Another option would be to utilize liquid hydrogen, installing liquid hydrogen storage tanks and vaporizers at the fleet operator's refueling facility. Liquefaction of hydrogen adds more to the cost, but opens up larger geographic areas. This is because liquid hydrogen can be transported economically by cryogenic tanker truck up to a thousand miles away, while gaseous hydrogen pipelines are generally limited to a few tens of miles and, even then, only for very large consumers.

The hydrogen infrastructure problem also could be alleviated by developing small-scale hydrogen generators, small-scale electrolyzers, or small-scale fuel processors, such as steam methane reformers. These hydrogen generators might supply just one or two vehicles — such as a home electrolyzer — or they might supply hydrogen on-site for a 50- or 100-car fleet. Or a local steam methane reformer might supply several fleets within a given area.

The small-scale hydrogen appliance option essentially takes advantage of two very robust energy infrastructures: the natural gas pipeline system and the electrical power grid. The hydrogen would be produced where it is needed, instead of at a central facility, with no need for building any new fuel transportation infrastructure. While the hydrogen would initially cost more due to the poor economies of scale, at least one analysis has shown that small-scale hydrogen generators could be cost-effective, particularly if produced in large quantities.

If successful, these small-scale hydrogen generators could grow in parallel with the hydrogen vehicle market. The gas industry could plan its investments to match the growth of the hydrogen vehicle industry, and the automobile manufacturers could ramp up their production, confident that a hydrogen supply would be available when and where needed, thereby significantly reducing the risks for both industries.

Early hydrogen-fueled vehicles will necessarily be confined to local areas due to lack of fueling facilities. Hydrogen-fueled vehicles would be sold to fleets and would also be used by commuters within urban areas plagued by air pollution. Since many families in the developed nations have two or more vehicles, they can designate one clean hydrogen car for in-city use and one for the relatively rare long-distance trips. Once islands of hydrogen fueling stations are in place, the next step would be to install hydrogen-fueling stations along major highways. These hydrogen-corridor stations would then open up the long-distance market for hydrogen-fueled vehicles.

The appropriate combination of hydrogen infrastructure options will depend strongly on the type of hydrogen onboard storage. If the vehicles store gaseous hydrogen, all four infrastructure options are available. If the vehicles store liquid hydrogen, then the small-scale hydrogen generator option is eliminated, and the early hydrogen vehicles would have to be supplied by excess capacity from existing liquid hydrogen plants. Economics will ultimately decide between gaseous or liquid onboard hydrogen storage, assuming that the public perceives either option to be equally safe.

Proponents of onboard liquid hydrogen contend that liquid hydrogen has fewer risks, but at least one merchant gas supplier considers liquid hydrogen handling to be more complex, with a higher safety risk. At the present time, however, no U.S. automobile manufacturer is actively developing onboard liquid hydrogen storage systems. General Motors is pursuing methanol, Ford is assessing both gaseous and liquid hydrogen onboard storage, and Chrysler initially evaluated gaseous hydrogen but is now considering liquid hydrocarbon fuels with an onboard fuel processor to make hydrogen. BMW is the only major automobile manufacturer actively developing and testing liquid hydrogen passenger vehicles.

***Recommended Action Items***

1. *Hydrogen Infrastructure Demonstration Project*

NHA members should consider a hydrogen infrastructure development and demonstration project (presumably including government cost-sharing) that would analyze and compare three options for providing cost-competitive gaseous hydrogen for early hydrogen vehicles:[12] a liquid hydrogen storage and vaporizer dispensing system using trucked-in liquid hydrogen from existing merchant hydrogen plants; a small-scale electrolyzer and compressor dispensing system; and a small-scale steam methane reformer (or other appropriate fossil fuel processor), gas cleanup, compressor, gaseous storage and dispenser system.

2. *Identify Prime Hydrogen Vehicle Demonstration Sites*

The National Hydrogen Association, as a service to its members and to other companies or organizations that may wish to participate in hydrogen vehicle demonstration projects, should assemble a list of appropriate hydrogen vehicle demonstration sites or regions. This list should take into account for each site the clean air incentives, any local or state clean air mandates, the local price of off-peak electricity, the local price of natural gas, the local price and availability of excess merchant hydrogen, the local renewable energy resources, the proximity of any centrally fueled vehicle fleets to those sources of excess merchant hydrogen, and, if possible, an assessment of the local fire marshal or regulatory agency regarding hydrogen vehicles.

**Overcoming the Safety, Codes, and Standards Barrier.** Dealing with safety is in one sense more difficult than handling technical hurdles such as cost or infrastructure, since we must deal with both the reality and the perception of safety. A hydrogen system may be engineered to be far less risky than existing gasoline-powered vehicles, but, if the public (or the insurance industry) *perceives* a hydrogen vehicle to be unsafe, then the hydrogen energy industry will remain a dream. So we must deal with both the reality and the perception of safety.

Safety must be paramount in all hydrogen activities. The infant hydrogen energy industry cannot afford even one accident. Every project should be thoroughly scrutinized, preferably with a review by recognized hydrogen safety experts, before construction begins. Technical safety issues — such as the development of fuel cell compatible odorants for hydrogen versus the use of hydrogen sensors and active ventilation, especially for residential garages — must be resolved.

Assuming that the hydrogen industry solves these technical issues, the question of public perceptions will remain. Education is the best antidote, and both DOE and the NHA have been active in promoting public education, most recently by supporting the Hydrogen 2000 documentary film project. These activities must continue to pave the way for the hydrogen energy industry.

The National Hydrogen Association has also taken the lead in establishing three separate groups to pursue developing codes and standards for gaseous hydrogen. (The International Standards Organization is currently developing codes and standards for liquid hydrogen vehicles.) These groups are modeled after the natural gas vehicle industry, covering onboard high pressure gas storage, the refueling connectors, and the refueling station itself.

***Recommended Action Items***

1. *Hydrogen Safety Review*

The National Hydrogen Association should recommend that a panel of hydrogen safety experts review all hydrogen energy projects. While NHA does not have the resources to implement a formal Hydrogen Safety Review Board, the NHA should recommend appropriate hydrogen safety experts to potential hydrogen energy project managers. The U.S. Department of Energy should set aside funds to devote to safety studies for each demonstration project. Current ISO Draft standards should be incorporated into these safety studies and the strengths and weaknesses of those standards should be reported on.

2. *Home Garage Safety Analysis*

Industry should analyze and recommend the appropriate safety measures for hydrogen vehicles parked in home garages. The project should demonstrate the safe operation of hydrogen leak detectors, ventilation systems, and other remedies.

3. *Codes and Standards Development*

The U.S. Department of Energy should continue funding the NHA Codes and Standards development project.

4. *Public Education*

Both the National Hydrogen Association and the U.S. Department of Energy should continue their public education activities, since public acceptance of hydrogen as an energy carrier is essential for the hydrogen energy industry.

**Overcoming the Onboard Storage Barrier.** The onboard storage barrier is one of perception more than reality. There are two technically and economically feasible onboard hydrogen storage options for the private passenger vehicle: liquid hydrogen and compressed gaseous hydrogen storage. Both are acceptable, and both can be designed into full-performance passenger vehicles. Other hydrogen storage options suggested over the years are either too immature, too heavy, or too costly, but the transportation industry only needs one viable hydrogen storage and fuel supply option. Other hydrogen storage options including metal hydride or carbon adsorption systems are available for larger vehicles such as trucks or buses, or in other niche applications that do not have the weight limitations or range requirements of conventional passenger vehicles.

The only significant disadvantage of high-pressure, compressed-hydrogen storage is large volume. The 5,000 psi hydrogen tank currently proposed might occupy three to four times the volume of the gasoline tank it replaces for the same range. But if the total power train system (fuel cell or hybrid internal combustion engine plus electric motor, gear box, and hydrogen storage) can fit into approximately the same space as the conventional power train (internal combustion engine, transmission, exhaust system, and gasoline tank), then a vehicle can be designed to meet the expectations of the driving public. The key is a ground-up vehicle design. The vehicle should be designed to accommodate the hydrogen-fueled power train, not the other way around.

A liquid hydrogen storage system occupies less space than one for gaseous hydrogen, but requires inherently more expensive hydrogen due to the cost of liquefaction. Liquid hydrogen also may suffer from boil-off — a vehicle parked for a week could lose substantial fuel — but proponents of this approach claim to have reduced boil-off to acceptable levels.

### *Recommended Action Items*

1. *Compressed Hydrogen Tank Qualification Tests*

High pressure (5,000 psi) hydrogen fiber-wrapped composite tanks must be qualified under NGV-2 tests (suitably modified for hydrogen) for use on public roads.[13] The National Hydrogen Association, working with the automobile manufacturers and tank manufacturers, should take the lead in qualifying these tanks for onboard vehicle use.

2. *Compressed Hydrogen Connector Tests*

Similarly, high-pressure connectors for storage tanks must be qualified under (modified) NGV-1 certification tests. Again, the NHA, working with automobile manufacturers and connector manufacturers, should take the lead in qualifying these connectors for public motor vehicle use.

**Overcoming Cost Barriers.** Much progress has been made in reducing the cost of key hydrogen energy system components, such as fuel cells and storage tanks, through ongoing research and development projects. Several studies under the DOE Hybrid and Fuel Cells for Transportation Programs with the automobile manufacturers have shown that complete fuel cell systems for vehicles could be nearly cost-competitive with conventional vehicles in large-volume mass production. Other studies have shown that hydrogen used in fuel cell vehicles and possibly in hydrogen-ICE hybrid vehicles could be competitive with gasoline per mile driven under appropriate circumstances. But much work remains to firm up these paper calculations, both for hydrogen vehicles and for the hydrogen infrastructure.

Building the small-scale hydrogen generators recommended above, under the infrastructure program, would help to refine cost estimates for producing hydrogen in small quantities specifically for the transportation market.

One essential element of this commercialization plan is to establish reliable estimates for hydrogen energy system component costs in large-volume mass production. Today's costs are almost irrelevant. For example, current low volume, virtually hand-manufactured fuel cells may cost US$3,196/kW or more. Yet several studies have predicted mass production costs of less than US$53 /kW for fuel cell systems, given their relative simplicity and low-cost materials (now that platinum loadings have been reduced to acceptable levels). We need to substantiate these estimates and extend the analysis to other hydrogen components, including onboard storage tanks, peak power augmentation devices, etc. Fortunately, the other major fuel cell vehicle and hydrogen-ICE hybrid vehicle components — such as electric motors, controllers, and peak power augmentation devices — are being developed under other DOE and industry programs for battery-powered electric vehicles. The fuel cell vehicle program must keep abreast of the latest developments in electric vehicle components.

Similarly, the mass production costs for the small-scale hydrogen appliances must be developed. Some estimates have been made for small-scale electrolyzers and small-scale steam methane reformers, but this work needs to be scrutinized by industry and extended to other infrastructure components including low-volume, high-pressure hydrogen compressors, gas cleanup devices, stationary storage tanks, and dispensing and safety equipment.

***Recommended Action Item***

*Continued Mobile Fuel Cell and Other R&D*

Research and development of key hydrogen transportation components should continue, with special emphasis on reducing manufacturing costs in large production volumes, including complete fuel cell systems, hydrogen-ICE hybrid systems, onboard hydrogen storage systems, stationary small-scale electrolyzers and steam-methane reformers, stationary hydrogen compressors, and hydrogen dispensing and safety equipment.

**Overcoming the Return on Investment Barrier.** The U.S. Department of Energy is currently funding a systems analysis project to begin making long-term estimates of industry return on investment (ROI) under various scenarios of hydrogen vehicle market penetration. Separate ROI estimates are being made for the gas industry and for the automobile industry. Ultimately, each company must meet its own economic criteria along with many other factors before deciding to enter the marketplace. But the transportation market requires two disparate industries — vehicles and fuel suppliers — to effectively make joint business plans for an entirely new technology.

Furthermore, the two industries have to be concerned with their bottom lines rather than the environment or oil imports, so the government needs to separately evaluate the societal impact of these hydrogen transportation market penetration scenarios. Hence the need for a coordinated systems analysis encompassing all three entities: vehicles, fuel supply, and society. Hopefully, the projections of ROI from these government-funded studies will be sufficiently credible and sufficiently profitable to entice the appropriate companies to make their own business plans and to then decide to participate in the hydrogen energy development program.

**Overcoming the Insurance Barrier.** Lack of insurance has curtailed some recent hydrogen project activities and forced others to rely on self-insurance by large corporations participating in the project. Insurance may become even more difficult to obtain as the public is exposed to hydrogen. One key approach may be to interest one or more insurance companies to become involved with the hydrogen energy business as a hedge against global climate change. The insurance industry has been among the first to recognize the consequences of climate change, since their liabilities rise with each new, weather-related disaster. Some may be very interested in working with the hydrogen energy industry to pave the way for the Hydrogen Energy Economy.

***Recommended Action Item***

*Seek Insurance Company Partners*

The National Hydrogen Association should actively seek out one or more insurance companies and encourage them to become active in developing the hydrogen energy insurance business. The NHA should assemble appropriate event data to distribute to possible insurance company partners.

## Overcoming Fixed Power Plant Market Barriers

As discussed previously, the fixed power plant market has fewer barriers than the transportation market, but also fewer rewards in terms of meeting environmental and oil import objectives. The primary barriers are cost, low or uncertain return on investment, and, in the case of remote village power, financing for overseas projects. Many of the market entry barriers have already been addressed, since one manufacturer has placed more than 65 of its 200-kW fuel cell systems in operation around the world. Although this phosphoric acid fuel cell system may provide limited technological spin-off benefits for the automotive PEM fuel cells currently under development, many — if not all — of the codes, standards, and siting issues have been favorably resolved.

**Overcoming Fixed Power Plant Cost and ROI Barriers.** As with mobile fuel cell systems, government research is justified to reduce the cost of natural gas-powered fuel cell systems for utility applications, including both hardware development and systems analysis. Stationary fuel cells must be more durable than mobile fuel cells, although they experience far less vibration, shock, or temperature swings than their mobile counterparts. The stationary PEM fuel cell system also requires an inexpensive gas cleanup system that is not required in the existing commercial phosphoric acid stationary fuel cell system. Both the natural gas reformer and the gas cleanup system developed for this application will have direct benefits for small-scale hydrogen generators for the transportation market.

The stationary fuel cell system will be most economical if the customer can utilize the waste heat from the unit. Since these systems are small, silent, and nonpolluting, they can be located on the customer's site, offering the possibility of cogeneration (both heat and electricity can be supplied to the customer). Additional systems analysis may be justified to quantify the advantages of cogeneration in the distributed utility market. These analyses also would provide potential suppliers of stationary fuel cell systems with greater confidence in projecting adequate return on investments.

***Recommended Action Item***

*Stationary Fuel Cell R&D*

Research and development of completely renewable hydrogen compatible stationary fuel cell systems should continue, with emphasis on appropriate Codes and Standards for their use.

**Overcoming Market Barriers to Remote Power Hydrogen Storage Systems.** This hydrogen commercialization plan assumes that renewable energy system markets will grow substantially in the years ahead, primarily in the developing world or other remote areas away from an electrical power grid. As intermittent renewable energy systems grow, so will the demand for inexpensive energy storage. This plan calls for the parallel development of inexpensive hydrogen electrolyzers, stationary hydrogen storage systems, and fuel cells to regenerate electricity when needed. Three elements are recommended to overcome barriers to using hydrogen for off-grid applications: hardware development, systems analysis, and dissemination of hydrogen storage benefits to renewable energy system suppliers and others.

Since the largest market for remote hydrogen storage may be in developing countries, financing and maintenance may be difficult. Early demonstration projects should, therefore, be sited on more friendly territory, with greater access to capital and also better maintenance capability. Alaska has already been identified as a likely location, having many remote villages supplied by very costly diesel power. Other possible areas include resort islands, such as those in the Caribbean that can afford to pay for reliable power and value low-pollution alternatives. The growing eco-tourism market may be a good avenue for transition village power systems.

***Recommended Action Items***

1. *Hydrogen Storage System R&D*

Industry should develop a remote hydrogen storage system (electrolyzer/storage/fuel cell) to be compatible with intermittent renewable energy systems (PV, wind, solar thermal, etc.).

2. *Remote Village Hydrogen Storage Demonstration Project*

NHA should coordinate a remote village hydrogen storage project in concert with an intermittent renewable energy project and appropriate international funding agencies. The NHA also should develop a catalog of likely sites for early renewable hydrogen storage demonstration projects, considering renewable energy availability (solar and wind) and local electricity prices (e.g., Alaska, resort islands, etc.).

## Summary of the Hydrogen Commercialization Plan

The National Hydrogen Association hydrogen commercialization plan is based on the premise that hydrogen will eventually become the storage mechanism for intermittent renewable energy in a sustainable energy future. Hydrogen also will become the dominant energy carrier for transportation, even if it is initially produced from natural gas or other fossil fuels.

In the transition period, before fossil fuels become too expensive due to some combination of environmental damage or scarcity, hydrogen will be used only as an energy carrier when and where it is cost-effective. Government mandates or incentives can ease the transition to clean fuels like hydrogen for the short-term, but hydrogen must ultimately succeed in the marketplace on its own without any government involvement. The NHA hydrogen commercialization plan is a market-oriented approach, based on three market entry points:

- Hydrogen-powered vehicles
- Natural gas-powered stationary distributed power generation
- Remote village renewable hydrogen storage

The hydrogen-powered fuel cell vehicle, or possibly the hydrogen-ICE hybrid vehicle, are the only hydrogen markets that are projected to be cost-competitive or nearly cost-competitive with the existing fossil fuel alternative (gasoline-powered vehicles) while simultaneously offering major reductions in urban air pollution, oil imports, and greenhouse gas emissions. This economic advantage is due to the 2.0 to 2.7 times greater energy efficiency[14] of the fuel cell vehicle compared to the internal combustion engine. This efficiency more than overcomes the 30 percent energy loss when converting natural gas to hydrogen, and the 1.5 to 1.8 times greater efficiency for a hydrogen-ICE hybrid electric vehicle. No other near- or mid-term hydrogen application provides these advantages without assuming major increases in the cost of fossil fuels.

The natural gas-powered stationary fuel cell system also is projected to be cost-competitive with the alternative, especially for co-generation applications where the customer utilizes the waste heat from the fuel cell. This fuel cell electrical generator does not have the same societal advantages as the fuel cell vehicle, since it does not reduce oil consumption. It does not reduce local air pollution or greenhouse gas emissions as much. But the stationary fuel cell has the advantage of helping to develop fuel cell technology, which may assist fuel cell vehicle technology. The natural gas-powered stationary fuel cell will help to reduce the manufacturing cost of steam-methane reformers and gas cleanup systems, both of which will be needed to supply hydrogen for the hydrogen vehicle market.

This stationary application is, therefore, primarily a stepping stone to assist in the development of the primary market: the hydrogen-fueled vehicle.

The natural gas reformers that supply hydrogen to stationary fuel cells are sized to meet peak electrical demand. That means there is excess hydrogen production capacity at all other times. Integrating a stationary fuel cell with a hydrogen vehicle refueling station can be done with minimal added capital cost.

The remote village hydrogen storage system comes much closer to the hydrogen energy industry vision of all energy supplied by renewable energy. However, renewable energy is usually too expensive to compete head-on with fossil fuel generated power in the developed world. Although wind power is cost-effective in some areas, the electrical grid serves as the effective storage medium; hydrogen cannot compete with grid storage. In remote off-grid locations, however, batteries are currently the primary storage medium, with noisy and dirty diesel engines as backup. The delivered cost of diesel fuel is very high in some remote locations. The plan, therefore, calls for the development of hydrogen storage systems to compete with battery storage, starting in high-priced, off-grid markets, such as in Alaska or on resort islands. This market will become the true link to a renewable hydrogen future.

The hydrogen commercialization plan includes both long-term goals and short-term action items that will start us down the road toward the hydrogen energy industry. The most important short-term activity is the development and demonstration of a viable, cost-effective hydrogen fueling infrastructure. The automobile industry will not start mass-producing hydrogen vehicles until it is convinced that hydrogen will be available when customers drive up to the pump. We believe that some combination of the four elements of this hydrogen infrastructure development plan (hauled-in liquid hydrogen, small-scale steam-methane reformers and small-scale electrolyzers, fleet applications, and hydrogen corridors) will provide the necessary hydrogen infrastructure for hydrogen-fueled vehicles. The other two key action items are safety and business planning issues.

We have not had the resources to cost out this plan. It should be considered a skeleton, outlining the direction, with details to be filled in as a result of both NHA activities as well as through ongoing and newly proposed activities by the U.S. Department of Energy and its counterparts around the world.

[1]Nonhybrid internal combustion engine vehicles operating on either neat hydrogen or mixtures of hydrogen and natural gas will play a role in early niche markets, since they offer the promise of lower emissions to help meet local air pollution goals. But without the boost in efficiency and significantly reduced emissions offered by hybrid or fuel cell vehicles, it would be very difficult to compete with other alternative fueled vehicles in the long run.

[2]Although we refer frequently to the U.S. Department of Energy Hydrogen Program, the National Hydrogen Association includes many industrial members outside the United States; the hydrogen energy industry will be an international development. Many of the DOE references apply to other government energy agencies throughout the industrialized world.

[3]All price goals are in 2000 U.S. dollars. The Producer Price Indexes of Finished goods and Crude energy Materials through June 2000 were used to calculate changes

[4]The primary alternative for the ZEV market is assumed to be the battery-powered electric vehicle, so this goal assumes that hydrogen-fueled vehicles are competing only against battery vehicles, giving the hydrogen-fueled vehicle great competitive advantage in terms of weight and range. Assuming that the California ZEV requirements resume in 2003, the total ZEV market could reach 15 percent of all new vehicles by 2010, including the original five opt-in states. This hydrogen goal, therefore, could reach 7.5 percent of all new vehicle sales. For comparison, the current DOE Hydrogen Program goal states that 25 percent of *all* new vehicles be hydrogen-powered by 2010, which implies sales on the order of two million hydrogen-powered vehicles annually.

[5]The hydrogen for stationary fuel cells will undoubtedly be derived onsite from natural gas initially, leading some to question whether such “natural gas systems” are appropriate for NHA and DOE hydrogen energy program support. However, these fuel cell systems will help to develop low-cost, small-scale, steam-methane reformers that may be essential to providing inexpensive hydrogen for fuel cell vehicles. Stationary fuel cell developments also may advance the technology for transportation fuel cells. Both are worthy hydrogen energy objectives.

[6]Daimler-Benz had to use compressed hydrogen in its first two prototype fuel cell vans, since development of an onboard chemical processor to produce hydrogen from methanol is a major technological challenge. Packaging compressed hydrogen tanks into a passenger van proved significantly less challenging than installing an onboard chemical factory.

[7]Methanol, although derived exclusively from nonrenewable natural gas at this time, could be produced by gasification of biomass or municipal solid waste. Hydrogen can also be produced from biomass and MSW with higher efficiency and lower cost. And, unlike hydrogen, methanol cannot be made directly from solar energy, wind, or hydroelectric power. Therefore, a methanol-based energy system would significantly limit our options as the world moves toward energy sustainability.

[8]Assume that the electric and gas utilities are handled by the same company. If not, then cooperation is still required between the electric utility and the gas utility, but this

cooperation is trivial compared to the coordination required between hydrogen suppliers and automobile manufacturers.

[9]In fact, greenhouse gas emissions could increase if stationary fuel cells displaced advanced gas turbines, since the combined efficiency of the natural gas reformer needed to produce hydrogen (70 percent) and fuel cell (55 percent) could be lower (e.g., 38 percent) than the efficiency of a natural gas turbine (e.g., 43 percent).

[10]Hydrogen used in the chemical industry may not be directly suitable for transportation applications. In particular, the hydrogen stream may contain impurities and water vapor that would have to be removed at added expense before being compressed and stored for transportation purposes.

[11]The primary stationary fuel processor is expected to utilize steam-methane reforming. However, other stationary hydrogen generators might use partial oxidation (no catalysts or steam) or autothermal reforming (downstream catalysts plus steam) of heavier hydrocarbons including methanol, ethanol, gasoline, naptha, or heavy oils. In addition, the DOE's Office of Transportation Technology is actively supporting onboard liquid hydrocarbon processors to provide the hydrogen for fuel cell vehicles. The NHA commercialization plan does not endorse these onboard fuel processing programs since they would not directly promote our end goal of a sustainable hydrogen energy industry, nor do they maximize societal objectives of reduced air pollution, greenhouse gas emissions, or reduced oil imports.

[12]We assume here that initial hydrogen-fueled vehicles in the U.S. will use gaseous hydrogen, since no U.S. company or the DOE is actively developing liquid hydrogen storage systems at this time, although at least one company is assessing the use of liquid hydrogen. See the section below regarding onboard storage for recommendations on liquid onboard storage.

[13]The U.S. Department of Transportation has approved fiber-wrapped composite tanks with a safety factor of 2.25 for use with natural gas vehicles at 3,600 psi. Certification at 5,000 psi should be routine, but these stronger tanks would probably have to pass the natural gas vehicle testing procedures (NGV-2) before DOT would consider certification.

[14]On a lower heating value basis.