Making Sense of Hydrogen

The Potential Role of Hydrogen in Achieving a Clean, Sustainable Transportation System

National Association of State PIRGs

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Executive Summary

The use of hydrogen as a fuel for cars and trucks has been touted as an environmentally responsible way to end America's dependence on foreign oil. However, a transition to a "hydrogen economy" —if poorly executed—could extend America's dependence on fossil fuels and nuclear power, while doing little to solve the severe environmental problems caused by our dependence on polluting and dangerous sources of energy.

As the nation and various states begin to engage the policy issues posed by hydrogen, it is critical that they do so carefully—proceeding with proven near-term strategies that reduce fossil fuel dependence while ensuring that any eventual transition to a hydrogen-based transportation system adequately protects America's future economic and environmental health.

America's inefficient use of fossil fuels threatens our economy, our environment and public health.

- Experts predict that, at current rates of growth in consumption, the worldwide production of oil will peak sometime within the next 35 years, and possibly by the end of the decade. When that peak occurs, supply will no longer be able to keep up with demand, triggering price increases and shortages.
- Domestic production of natural gas has failed to keep up with growing demand in recent years, despite a dramatic increase in the number of operating natural gas wells. Natural gas prices have doubled since 1995 and will likely remain high for the near future.
- Fossil fuel consumption in automobiles poses significant environmental and public health threats. Motor vehicles are responsible for more than a quarter of the nation's emissions of smog-forming pollutants and health-endangering particulates. America's transportation system emits more global warming gases than the entire economy of any other nation in the world except China and possibly Russia.
- Coal and nuclear power are unacceptable long-term solutions to the nation's energy problems. The extraction and combustion of coal cause devastating environmental and public health problems, while nuclear power remains

an extremely risky and expensive source of energy.

Hydrogen fuel is neither inherently renewable nor inherently clean.

- Hydrogen does not exist by itself anywhere in nature. Instead, it must either be extracted from other fuels (such as natural gas or biomass) or extracted from water using electricity.
- The National Academy of Sciences estimates that creating hydrogen from renewable energy sources is likely to be more expensive than creating it from natural gas, coal or electricity in the near term. However, the NAS notes that:
    - Using coal or electricity from today's electric grid to create hydrogen is likely to release as much global warming-inducing carbon dioxide as burning gasoline in efficient hybrid-electric vehicles (in the absence of as-yet-unproven technologies to capture and store carbon dioxide underground or in ocean waters).
    - Dependence on natural gas as a source of hydrogen would likely lead to an increase in imports—replacing our nation's dependence on imported oil with a dependence on imported natural gas.
- Generating hydrogen from renewable sources of energy would be virtually emission-free. But the cost of renewably generated hydrogen—at least in the short-term—is far greater than the cost of generating hydrogen from other sources. And using solar or wind power to replace the dirtiest forms of electricity generation in the short term would be less expensive and achieve greater reductions in carbon dioxide emissions than using them to generate hydrogen to power vehicles.
- Renewable generation of hydrogen—or the use of other renewable fuels for transportation—is essential for the long-term sustainability of the U.S. transportation system. Even if the average fuel use or global warming emissions from U.S. motor vehicles were to be sliced in half immediately, continuing the recent rate of growth in vehicle travel would result in a return to current emission levels by 2027. Renewable energy is the only alternative that can achieve a breakthrough in the reduction of global warming emissions from transportation.

If hydrogen is produced from renewable sources of energy, it could alleviate our nation's reliance on fossil fuels and nuclear power and reduce the environmental impacts of our transportation system.

To ensure that hydrogen can contribute to a clean, sustainable transportation future, we must employ "win-win" strategies that reduce our reliance on fossil fuels in the short term, while paving the way for renewable energy to power the nation's transportation system in the future.

1. Make Today's Cars Cleaner and More Efficient

- A variety of analysts have estimated that the nation's cars and trucks could achieve 10 to 50 percent better fuel economy at minimal increase in costs using technologies that either exist now or will be on the market soon.
- Similar improvements are possible for reducing vehicle emissions. More than 20 models of partial zero-emission vehicles—each of which emits about 90 percent less pollution than today's new cars—are now available in California and selected other states.
- State governments can encourage improvements in vehicle emission

control technology by adopting California's stringent-yet-achievable standards for health-threatening pollutant emissions and the introduction of advanced vehicle technologies. Governments at all levels can use tax and other incentives to encourage the purchase of cleaner vehicles.

2. Develop Renewable Energy

- Increasing the amount of electricity generated from renewable sources would reduce the environmental impacts of our electric system, reduce our dependence on fossil fuels and nuclear power, and bring down the price of renewables in the future, making a transition to a truly renewable hydrogen future more easily attainable.
- Governments can promote renewable energy through the adoption of renewable energy standards for electricity generation and standards for the integration of renewable energy in building design, the creation of renewable energy funds, the adoption of tax credits for renewable generation, and the removal of barriers to the installation of clean, small-scale distributed generation technologies, including stationary fuel cells.

3. *Pave the Way for a Renewably Powered Transportation System*

- Government can play a role in encouraging basic research into vehicles and fuels with the potential to operate on renewable sources of energy, including hydrogen-powered and battery-electric vehicles and vehicles that operate on biomass fuels.
- Governments should not invest in the development of hydrogen fueling stations powered by non-renewable forms of energy. In addition, government should work to steer private-sector investment toward measures that move toward renewable generation of hydrogen. While the development of fueling stations based on natural gas might have short-term environmental benefits and ease the introduction of hydrogen powered vehicles, public money and effort would be best focused on solving the technical problems facing hydrogen-powered and other zero-emission vehicles and on supporting the development of renewable hydrogen technologies.
- State and local governments should also monitor the progress of safety codes and standards for hydrogen, adopting and enforcing them once they are promulgated. Governments should also open discussions with businesses, non-profit organizations and others to plan the future transition to a renewably powered transportation system.

Governments should not take actions that encourage the generation of hydrogen from environmentally damaging sources of energy.

- Government must not support efforts to derive hydrogen from environmentally damaging sources—such as the coal and nuclear-based hydrogen programs favored by the Bush administration—and should support the development of all vehicles and fuels with potential benefits for energy security and the environment, not just those that operate on hydrogen.
- Any hydrogen strategy that does not include progress toward cleaner cars in the near term, the expansion of renewable energy, and basic research into clean vehicle technologies—or that makes investments in technologies known to have major, negative environmental impacts—does not help to achieve the goal of a sustainable transportation system and should be avoided.

Introduction

America has become dangerously over-reliant on fossil fuels. Since 1950, consumption of fossil fuels in the United States has increased at roughly twice the rate of population growth.[1]

The implications for our economy, environment and national security are severe.

- The U.S. currently imports about 60 percent of its oil, which is notoriously volatile in price.[2] Increases in oil prices preceded eight of the nine economic recessions between World War II and 2000.[3] Most experts predict that global production of oil could peak sometime during the next three decades, causing price spikes and shortages.[4]

- Natural gas prices have doubled since 1995 as domestic production has failed to keep pace with increased demand—despite a dramatic increase in the number of working natural gas wells, and a dramatic increase in importation of liquified natural gas form overseas.[5] Federal Reserve Board Chairman Alan Greenspan has suggested increased importation of natural gas as a solution to rising prices—although importation brings with it increased costs, public safety threats and continued reliance on foreign sources for energy.[6]

- The extraction and combustion of coal is responsible for a range of devastating environmental problems—including acid rain, health-threatening particulate pollution, mercury deposition in waterways, and the destruction of land and water resources by coal mining. Coal consumption for the generation of electric power increased by 27 percent between 1990 and 2003.[7]

- The combustion of fossil fuels is responsible for the greatest threat facing the environment this century: global warming. The United States is the world's leading source of global warming gases—the vast majority of which are released through the combustion of fossil fuels. Indeed, global warming gas emissions from cars, trucks and other forms of transportation in the U.S. are greater than the total emissions of any other country in the world except China and possibly Russia.[8]

The use of hydrogen as a transportation fuel has been touted as a solution to some of these problems. Hydrogen is plentiful—the most abundant substance in the universe—and emits very little to no pollution when burned or used to create electricity in a fuel cell. Moreover, it is possible to generate hydrogen fuel using renewable resources such as solar, wind and biomass energy—allowing for the possibility of a clean, sustainable energy future.

But this sustainable, ecologically green vision of a "hydrogen economy"—held widely by environmentalists and those concerned about the nation's long-term energy security—is not the only potential path forward, nor, in the short term, is it the most likely one.

Hydrogen can also be created from fossil fuels—the same oil, natural gas and coal that are causing us economic and environmental problems today—as well as risky and expensive nuclear power. Creating hydrogen from fossil fuels is far from emission-free—indeed, some forms of hydrogen generation would create more global warming pollution than burning gasoline in highly efficient cars. Pursuing a "dirty hydrogen" path would perpetuate, rather than end, our dependence on fossil fuels and other dangerous sources of energy, and fail to solve the environmental problems posed by our transportation system.

Thankfully, we are still very early in what some believe will be an inevitable transition to a hydrogen economy. There is still time to ensure that hydrogen can deliver on its potential to reduce America's dependence on fossil fuels and help the environment.

This paper attempts to describe a vision for how we can achieve a clean hydrogen future while, at the same time, reducing the environmental and other threats posed by our current transportation system.

A "hydrogen economy" may appear to be a long way off. But our nation's future economic and environmental health depends on our ability to develop a transportation system that is primarily reliant on clean, abundant, renewable sources of energy. Hydrogen is just one potential vehicle for achieving that vision. The decisions government officials make today will have a significant impact on whether that future will be realized.

Hydrogen Basics

What Is Hydrogen?

Hydrogen is the most abundant substance in the universe. It is the simplest of all the elements—consisting of one neutron and one electron—and the lightest of all gases.

The hydrogen molecule—which consists of two hydrogen atoms (H_2)—is almost never found by itself in nature. Instead, hydrogen is bound with other elements in compounds such as water (H_2O) and hydrocarbons like those in biomass, natural gas, oil and coal. Unlocking hydrogen from these compounds requires the use of energy, generally in the form of heat or electricity.

Thus, hydrogen is one step removed from the energy sources that are used to create it—unlike oil, which can be pumped directly from the ground and burned in vehicles. In this sense, hydrogen is a lot like electricity—an ***energy carrier*** that can be used to make it more convenient for people to transport and use the raw energy contained in fossil fuels, biomass, sunlight, geothermal resources or the wind.

Why Would We Want to Use Hydrogen as a Fuel?

Hydrogen has several properties that make it a good energy carrier compared to some of the alternatives—as well as properties that make it difficult to use.

- **Hydrogen provides energy with low to zero emissions at the point of use.** When pure hydrogen is used in a fuel cell, the only emissions are water and heat. The use of hydrogen in an internal combustion engine produces some harmful emissions (particularly smog-forming nitrogen oxides) but fewer total emissions than engines running directly on fossil fuels.
- **Hydrogen is flexible in the sources of energy that can be used to create it.** Unlike gasoline, which can come from only one source—petroleum—hydrogen can be created from a variety of fossil fuels and renewable sources of energy. Moving toward the use of hydrogen for applications that are heavily reliant on a single fuel—such as motor vehicles—could allow for more diversification of energy sources.

- **Hydrogen is more easily stored than some other energy carriers, such as electricity** (though it remains more costly and difficult to store than liquid fuels such as gasoline and ethanol). Using hydrogen eliminates the need to rely on heavy, costly batteries that must be recharged frequently in applications such as electric vehicles and laptop computers. Hydrogen can also potentially be used to store excess energy that is produced from intermittent renewable power sources such as solar and wind power, thus allowing those sources to make a larger contribution to the nation's energy needs.
- **Hydrogen has an extremely high energy density by weight.** Thus, weight is not a barrier to the use of hydrogen in any application.

The main disadvantage of hydrogen as a fuel is that it has ***extremely low energy density by volume***. Unlike gasoline, which is a liquid at room temperature and atmospheric pressure, hydrogen is a gas that is lighter than air—lighter even than the helium used to inflate balloons. This makes hydrogen prone to leakage. It also means that, to store a reasonable amount of energy within a given volume, hydrogen must be stored at very high pressure, chilled to very low temperature, or bound up in compounds that will readily release the hydrogen for use. Compression or liquefaction of hydrogen both require significant amounts of energy and may require the use of special materials to prevent hydrogen from escaping. Experimentation with storing hydrogen in other compounds—such as metal hydrides—is continuing and may be more promising than either compression or liquefaction as a long-term storage solution.[9]

A second disadvantage of hydrogen is that it ***requires energy to create*** (and often, to store). The efficiency with which hydrogen can be generated has significant impacts on the degree to which a "hydrogen economy" would be feasible and beneficial.

How Can Hydrogen Be Generated?

Hydrogen can be "generated"—that is, extracted from other compounds—using one of several processes:

- **Reformation** – Hydrogen is reformed from natural gas or other fuels by exposing the fuels to high-temperature steam in the presence of a catalyst. The result of the process is hydrogen and carbon dioxide. A similar process can be used to create hydrogen from biomass.
- **Electrolysis** – By exposing water to an electric current, water can be split into its constituent parts—hydrogen and oxygen. Electrolysis requires a large amount of electricity.
- **Gasification** – Using a super-heated reactor, coal, biomass, or other fuels are turned into a gas, which is then exposed to steam and oxygen to create hydrogen, carbon monoxide and carbon dioxide.

Other methods of generating hydrogen are in the experimentation phase. At this time, however, one method of obtaining hydrogen—electrolysis—is emission-free at the point of production (though even electrolysis is responsible for "upstream" emissions resulting from the generation of electricity). Other methods produce significant amounts of carbon dioxide—the leading gas responsible for global warming —and other pollutants.

What Is a Fuel Cell?

Policy discussions involving hydrogen inevitably turn to fuel cells, which use hydrogen to create electricity. While fuel cells are not the only technology capable of making use of hydrogen fuel, they are the most efficient such technology.

A fuel cell uses an electrochemical process involving hydrogen and oxygen to create electricity. There are many types of fuel cells, but all share the same general operating principles. For example, in some types of fuel cells, hydrogen (or a fuel containing hydrogen) is exposed to a catalyst, which separates the hydrogen into electrons and positive ions. The ions pass through an electrolyte membrane, but the electrons cannot pass through, and instead travel along a circuit to create an electrical current. After passing through the membrane, the hydrogen ions combine with oxygen and electrons to create water and heat. (See Fig. 1.)

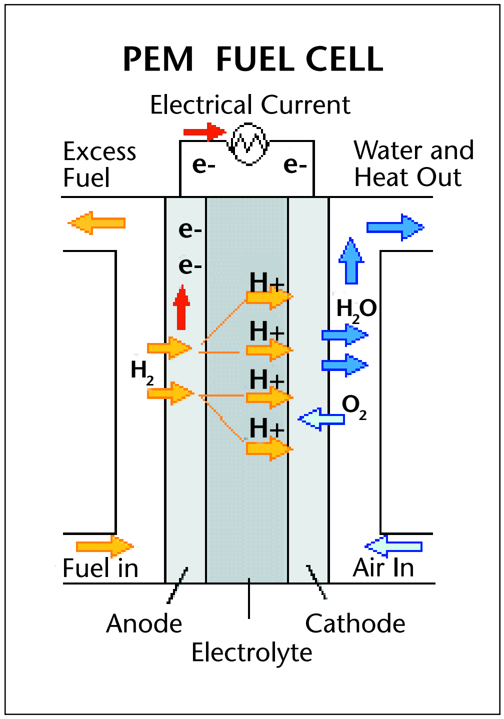
Do You Need Hydrogen to Use a Fuel Cell?

Not necessarily. There are several types of fuel cells that operate directly on a variety of fuels, including methanol, natural gas and even fuels made from coal.

These types of fuel cells, however, generally run at very high temperatures. ***High-temperature fuel cells*** are appropriate for many stationary applications—in buildings and power plants, for instance. But because they take a long time to warm up (and are often large and heavy), most are inappropriate for cars and most other transportation applications.

Low-temperature fuel cells—such as proton exchange membrane (PEM) fuel cells—are the most appropriate fuel cells for cars and trucks. Low-temperature fuel cells have a few drawbacks, though. First, they require pure hydrogen for operation and are very susceptible to "poisoning" by contaminants. Second, they require the use of very expensive catalysts, such as platinum. While scientists have succeeded in reducing the amount of catalyst needed in low-temperature fuel cells, the price and availability of platinum is still a major concern.

Fig. 1: Illustration of Proton Exchange Membrane (PEM) Fuel Cell[10]



The use of fuel cells in stationary applications poses a different set of problems and opportunities than the use of fuel cells in transportation. For example, it is possible to capture much of the waste heat from stationary fuel cells to generate additional electricity or to provide heat or hot water to businesses and residences—boosting the overall efficiency of stationary systems. In addition, because many stationary fuel cells can operate on fuels other than pure hydrogen, the infrastructure changes that would be needed to support stationary fuel cell applications may not be as great. On the down side, fuel cells still suffer from short operating lifetimes—a problem that is less severe for fuel-cell vehicles (which are only used for short periods each day) than for fuel cells used to generate electricity for homes and businesses.

In this paper, we will focus primarily on the use of hydrogen fuel cells in vehicles.

Are Fuel Cells the Only Way to Use Hydrogen in Vehicles?

In addition to fuel cells, hydrogen can be used in internal combustion engines (ICEs) similar to those that currently burn gasoline in vehicles. BMW and Ford Motor Company are among those pursuing this approach. Hydrogen ICEs emit few pollutants and are technologically simpler than fuel cells. Some view hydrogen ICEs as a short-term “bridge” technology to be used as technological progress proceeds on fuel cell designs. However, hydrogen ICEs do not demonstrate the same efficiency gains possible in fuel cells, reducing their economic and environmental attractiveness. Moreover, the development of hydrogen ICEs does not address the significant issues with the production, distribution and storage of hydrogen that may pose a greater obstacle to the arrival of a hydrogen economy than the development of fuel-cell vehicles themselves.

Credit: Electric Vehicle Association of Canada.

Fuel cell system in the Chrysler FCEV fuel-cell vehicle.

Hydrogen in Transportation

When Will Hydrogen-Fueled Vehicles Be Available to Consumers?

No one really knows when, or if, hydrogen fuel cell vehicles will be sold in large numbers to consumers. In part, this depends on the availability of refueling infrastructure for hydrogen. But it also depends on technological breakthroughs in the distribution and storage of hydrogen and in fuel-cell vehicles themselves. Finally, the schedule for deployment will depend on external factors, such as the price and availability of gasoline.

The most optimistic observers—including General Motors—believe that hydrogen fuel-cell vehicles will become generally available by around 2010.[11] The U.S. Department of Energy believes that even with a successful development effort, the information needed to make a decision on the commercialization of fuel cells in transportation and other applications may not be available until 2015, with fuel cell vehicles "hitting the showrooms" in 2020.[12]

Other industry observers believe that it will be 20 to 30 years, if then, before there is widespread commercialization of fuel cell vehicles.[13]

A small number of hydrogen fuel cell vehicles are already on the road in demonstration projects. Both Honda and Toyota began leasing a small number of vehicles for testing in California in late 2002. The California Fuel Cell Partnership—a public-private partnership—reports that 41 fuel-cell vehicles are currently operating in California.[14]

Hydrogen-fueled internal combustion engines could conceivably make it to market much more quickly. Ford is planning to place some hydrogen ICEs with government agencies for road testing by next year.[15]

What Are the Technological Barriers to Hydrogen-Fueled Vehicles?

Hydrogen-fueled vehicles are seen as an attractive alternative to other zero-emission vehicles (such as battery-electric cars) because they hold the promise of delivering the same performance quality as traditional gasoline-powered vehicles with no harmful emissions. But several technological hurdles must be surmounted for hydrogen-powered vehicles to deliver on that promise.

The most fundamental performance issues facing hydrogen vehicles are the related problems of fuel storage and driving range. Hydrogen storage poses a basic physical dilemma: vehicles must carry enough hydrogen on board to provide an acceptable driving range between fill-ups, yet must not carry storage tanks that are too large (reducing passenger or cargo room) or waste excessive amounts of energy in compression or liquefaction. In addition, they must be safe.

The Department of Energy has set a goal of developing hydrogen-powered vehicles capable of traveling 300 miles on a tank of fuel—a range similar to today's gasoline-powered vehicles.[16]

Several fuel-cell vehicle prototypes have achieved driving ranges of 200 miles or more before refueling. But there is strong skepticism among some observers as to whether the storage problem can be resolved using current technology. In a 2004 report, the National Academy of Sciences (NAS) concluded, "[T]he committee questions the use of high-pressure tanks aboard mass-marketed private passenger vehicles from cost, safety, and convenience perspectives. . . . The committee has a similar view of liquid hydrogen."[17]

The American Physical Society, in a 2004 statement, was even more blunt, concluding that "no material exists today that can be used to construct a hydrogen fuel tank that can meet the consumer benchmarks [established by the U.S. Department of Energy]. A new material must be developed."[18]

Some suggest that the hydrogen storage problem can be solved through the use of very high pressure tanks that can be molded to fit the shape of a vehicle—particularly if vehicle efficiency can be improved to the point that less on-board fuel storage is necessary. However, such an approach would likely increase the energy penalty incurred by the need to compress hydrogen to extremely high pressures, reducing the overall energy efficiency of the system.

Fuel-cell vehicles also face some unique problems, such as difficulty starting in extremely cold weather, problems with thermal management, durability problems, and limitations on the useful life of fuel cell systems. Engineers continue to work to resolve these performance issues.

> "No material exists today that can be used to construct a hydrogen fuel tank that can meet the consumer benchmarks [established by the U.S. Department of Energy]."
>
> — American Physical Society

Is Hydrogen Safe?

Hydrogen may be no more or less safe than gasoline—a notoriously flammable, explosive, and poisonous fuel. Fears that fuel-cell vehicles would be so many mini-Hindenburg disasters waiting to happen are overblown. (The fire that consumed the Hindenburg airship in the 1930s is now thought to have been caused by the dirigible's flammable exterior paint, not the hydrogen used to keep it afloat). But the widespread use of hydrogen would create a range of new and different safety issues that governments and individuals would need to address.

To begin with, hydrogen—like natural gas and unlike gasoline—is lighter than air and disperses quickly once released. Thus, leaking hydrogen will quickly spread upward and outward from the source of the leak, unlike gasoline, which will pool on the ground. In the case of a car fire, the quick dispersal of hydrogen is likely good news. Hydrogen's lightness is not entirely a good thing, however—in an enclosed space with poor ventilation, such as a garage, leaking hydrogen can pool under the roof, creating the risk of fire or explosion.

Unlike gasoline, hydrogen is non-toxic. But hydrogen is also colorless and odorless, meaning that one cannot detect a hydrogen leak by sight or smell. (Scientists are attempting to develop an odorant to add to hydrogen—similar to the odorants added to natural gas—to alert individuals to leaks. This has proven to be very challenging.) Instead, sensors must be employed to detect leaking hydrogen, adding yet another cost to hydrogen transportation systems.

Even more troubling, hydrogen burns with an invisible flame that emits very little radiant heat.[19] As a result, a person encountering a hydrogen fire might not realize the fire was there until he or she was in its midst. Hydrogen also ignites easily—at certain concentrations in the air, cellular phones or ordinary static electricity have the potential to set hydrogen afire.[20]

Thus, special care will have to be taken to ensure that hydrogen fueling and storage systems are safe. Again, the risks posed by hydrogen may be of no greater or lesser scale than gasoline, but they are different risks, and will require significant effort—particularly in the development of codes and standards—to address.

How Much Will It Cost to Buy a Vehicle that Runs on Hydrogen?

The first round of fuel-cell vehicles—which have been more or less custom designed and built—have been extremely expensive, leasing for as much as $10,000 per month.[21]

Those costs will certainly come down. The California Air Resources Board, which promotes fuel cell vehicles through a variety of programs, projects that the incremental cost of a fuel-cell vehicle (over and above a comparable gasoline-powered vehicle) will decrease to about $9,300 by 2012.[22]

Again, improvements in efficiency can make a difference by reducing the size of the fuel cell stacks needed to power vehicles. The smaller the fuel cell stack needed, the lower the likely cost. In addition, hydrogen internal combustion engine vehicles may be less expensive to manufacture and sell than fuel-cell vehicles. It is likely that early hydrogen vehicles—whether powered by fuel cells or internal combustion engines—will be hybridized. Thus, additional production of gasoline-electric hybrids in the near term would bring down the cost of what is likely to be an important technological component of hydrogen-powered vehicles.

How Will Hydrogen Vehicles Be Fueled?

There are three ways in which hydrogen can be condensed into a small volume: compression, liquefaction, and storage within other compounds—typically metal hydrides. These choices correspond to the potential ways in which hydrogen can be stored and dispensed to vehicles.

Of the three options, liquefaction appears to be the least likely choice for hydrogen refueling. To remain in liquid form, hydrogen must be kept at super-cold temperatures of less than -400° F (near absolute zero)—requiring the use of significant amounts of energy for refrigeration and making self-service refueling impractical. Even with these precautions, the fuel will "boil off" at a rate of about 3 to 4 percent per day, reducing the efficiency with which the fuel can be used.[23]

Most fuel cell demonstration vehicles have used compressed hydrogen. The greater the level of compression, the more energy is available to the vehicle. Compression also requires large amounts of energy, and the use of high-pressure hydrogen creates the risk of tank rupture in accidents—although new high-strength materials could reduce these risks substantially.

Several automakers have experimented with storing hydrogen in metal hydrides—solid or liquid compounds that yield hydrogen when exposed to a catalyst or to heat. Metal hydrides have the advantage of providing more energy-dense storage of hydrogen than either liquefaction or compression, but they are quite heavy. When the hydrogen supply in the metal hydrides is depleted, the hydrides are either replenished inside the vehicle (through refueling) or removed from the vehicle for recycling. Should metal hydrides have to be removed from the vehicle for replenishment, this would require a very different type of refueling infrastructure than that in place for gasoline vehicles today.

In addition to these methods, researchers are examining the potential to store hydrogen within carbon nanotubes—extremely minute, strong structures that can be designed to store large amounts of hydrogen in a small space. This research is at a very early stage but, if successful, would offer great potential.

How Will Hydrogen Be Distributed?

In broad terms, there are two potential models for how to distribute hydrogen fuel: centralized and decentralized systems.

Credit: Leslie Eudy, DOE/NREL

Hydrogen refueling station in Sacramento, California.

A centralized hydrogen distribution system would be similar to the system used to distribute gasoline today. Hydrogen would be produced at large-scale facilities—possibly in close proximity to biomass farms, coal fields, wind power installations, nuclear power plants or other sources of energy—then distributed to filling stations by pipelines and tankers. Hydrogen's low energy density again complicates matters: a tanker truck of a given size can carry less energy in the form of hydrogen than it can in the form of gasoline or other liquid fuels, potentially increasing transportation costs and reducing the energy efficiency of the entire process. Pipelines pose their own difficulties. While thousands of miles of hydrogen pipelines are currently in operation around the world, hydrogen pipelines are typically 40 to 100 percent more expensive to construct than natural gas pipelines.[24]

In a decentralized system, hydrogen would be produced at filling stations through either the reformation of natural gas or electrolysis of water. Eventually, perhaps, hydrogen could be created at homes from natural gas, electrolysis powered by solar energy or other sources. A decentralized approach takes advantage of existing national distribution networks for electricity and natural gas. The downside of this approach is that it misses out on economies of scale that could be gained from centralized production and makes the use of remote renewable sources of energy—such as wind energy from the American Plains—more costly and difficult.

Both centralized and decentralized systems would be expensive to create. The National Academy of Sciences, in a draft 2004 report, estimated that a decentralized filling station capable of serving 854 fuel-cell vehicles that refuel once a week would cost approximately $1.85 million in capital costs to construct, using current technologies. Future technologies could reduce the cost to $960,000 for a filling station serving the same number of vehicles.[25] A 2001 analysis conducted for the California Fuel

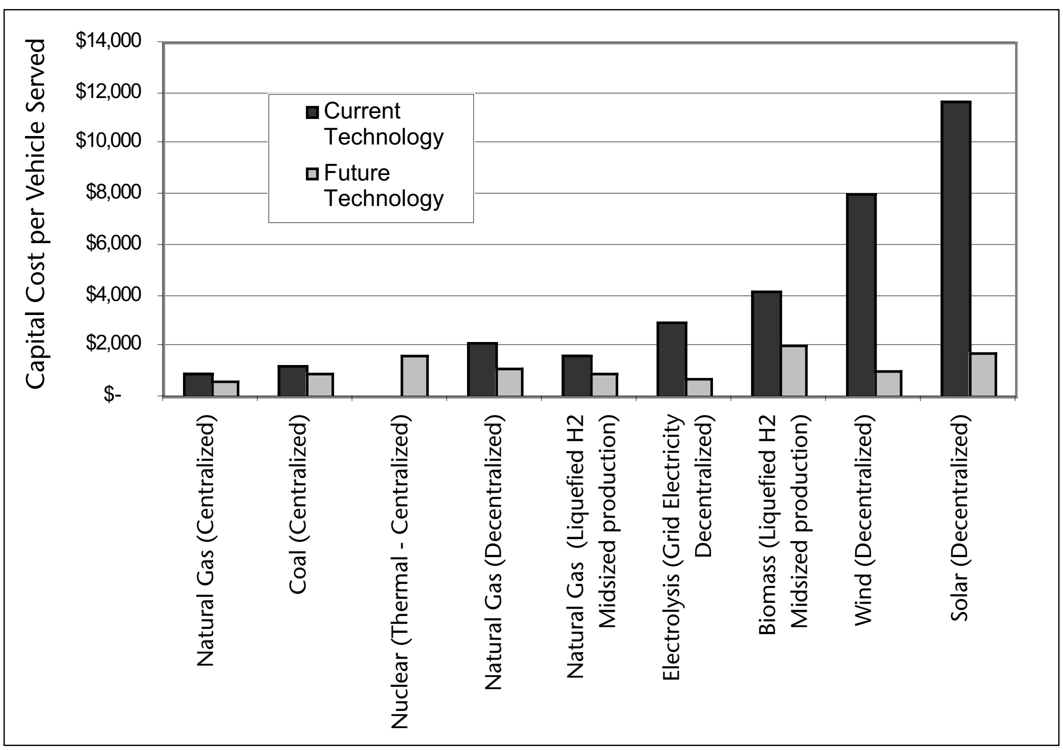
Cell Partnership estimated the cost of a similar fueling station capable of serving 400 vehicles at $450,000.[26] Another analysis conducted for the U.S. Department of Energy in 2002 estimated that a small natural gas-reformer system capable of supporting 183 vehicles would cost approximately $250,000 in capital expenditures.[27]

Despite the differences in the fueling systems studied and the resulting cost estimates, it is reasonable to assume that the initial capital cost of constructing hydrogen fueling stations in the near term is likely to exceed $1,000 per vehicle—not including infrastructure costs related to the production and delivery of natural gas to the fueling station. The capital investment needed to install a natural gas-based hydrogen fueling station would likely be more than four times the cost of installing a storage and dispensing system for conventional gasoline.[28]

Large-scale, centralized systems for producing hydrogen are more cost-effective on a per-vehicle basis. (Fig. 2 shows the per-vehicle capital costs of various hydrogen production and distribution infrastructure options, based on the NAS's cost estimates for current technologies and potential future technologies.) However, this is only true if the facilities are fully utilized. Since the centralized production systems evaluated in the NAS study serve in excess of 2 million fuel-cell vehicles, it will likely be decades before such economies of scale can be achieved.

Even a small-scale decentralized network to produce and distribute hydrogen will require significant capital investment. With the small number of fuel-cell vehicles likely to be on the road in the early years, it is likely that government will be asked to provide at least some of the initial capital. The degree to which such an investment would be a wise use of public dollars is a major question likely to face state and federal officials, and one to which we will return later.

Fig. 2. Infrastructure Capital Costs per Hydrogen Fuel-Cell Vehicle Served at Full Utilization[29]



Hydrogen: Economic and Energy Supply Implications

Why Are Automakers So Enthusiastic About Hydrogen?

Over the course of the last half-century, the automobile industry has generally refused to implement environmental improvements to their vehicles unless required by law. Why then are several automakers not only spending millions of dollars on research into hydrogen-fueled vehicles, but doing so enthusiastically?

The reasons likely have to do with the desire to stave off government regulation of fuel economy in the near term and the will to survive over the long term in a post-oil economy.

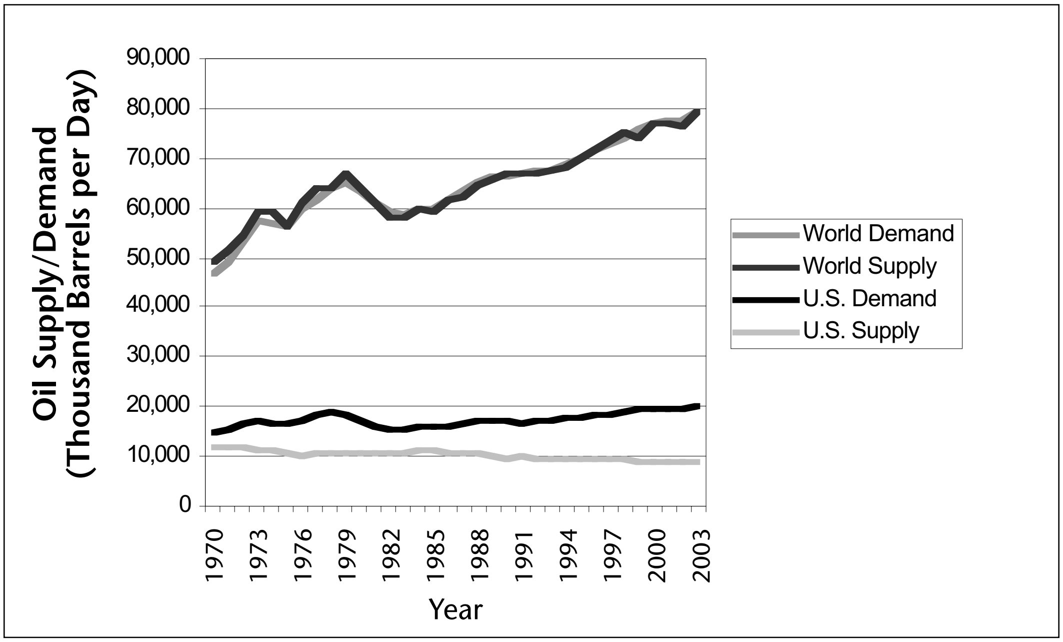
The viability of the automobile-centered transportation system in the United States and elsewhere rests on the availability of cheap (or at least reasonably affordable) oil. However, a growing body of evidence suggests that the era of inexpensive oil is drawing to a close.

The world is not about to "run out of oil" any time soon. But what will happen—almost certainly within the lifetime of children born today and possibly quite soon—is that production of oil will peak. That is, we will reach a point when we are unable to produce enough oil to satisfy growing demand. When that occurs, shortages will take place, prices will rise, and—if oil remains a significant source of energy—economic dislocation will result.

The problem is that no one knows exactly when this peak in production will occur. The U.S. Energy Information Administration, assuming growth rates in oil consumption similar to those at present, predicts that oil production is likely to peak around 2037—although, like all such estimates, there is a wide band of uncertainty.[30] Others suggest that peak production could occur much sooner—perhaps by the end of the decade.[31]

Regardless, should oil consumption continue to increase at a relatively steady clip (and the rapid industrialization of developing nations such as China and India suggests that it will), our dependence on oil as a transportation fuel will begin to have economic consequences in the foreseeable future. No industry has as much to lose from such a scenario as the automobile industry. As a result, there is a strong economic motivation for automakers to lay the groundwork for a future transition to a non-petroleum-based automotive fuel.

Fig. 3. U.S. and World Oil Supply and Demand[32]



Hydrogen has clear advantages over many of the alternatives, largely due to the variety of energy sources that can be used to create it.

Future oil scarcity is not the only economic motivation automakers face. Competitive pressures are important as well. Automakers are loathe to fall behind the technological curve set by their competitors—indeed, during the energy crises of the 1970s, American automakers that had focused on big, gas-guzzling vehicles were swamped in the marketplace by foreign competitors selling smaller, more efficient imported vehicles. If one automaker is seriously pursuing a path that could lead to massive technological change in the industry, therefore, all other competitors must at least consider following a similar path.

In addition, the growing economies of developing nations such as China may provide the next great market for motor vehicles—a market that each major automaker wishes to tap. Unlike the United States, China does not possess an entrenched gasoline-based transportation infrastructure. Should hydrogen prove workable as an automobile fuel, China could bypass the need to build a gasoline-based infrastructure entirely and move straight to hydrogen.[33] Given the economic potential for vehicle sales in the developing world, automakers want to ensure that they have the ability to compete in those markets.

Hydrogen-powered vehicles also have some potential advantages that may make them attractive to consumers. Like other electric-drive vehicles, hydrogen fuel-cell vehicles are quiet with greater low-end torque than conventional vehicles. Fuel-cell vehicles could conceivably be used as remote generators or back-up power supplies as well as sources of transportation. And the removal of the bulky internal combustion engine and conversion to "drive by wire" electronic controls could also allow for more flexible and adventurous vehicle designs.

Finally, regulatory policies on air pollution, energy efficiency and greenhouse gas emissions—particularly in nations that have ratified the Kyoto Protocol (a group that does not include the U.S.)—could push automakers toward hydrogen and fuel cells. China, for example, has announced plans to impose fuel economy standards on automobiles more stringent than those in effect in the U.S.[34]

Automakers, therefore, have a potentially strong economic interest in pursuing hydrogen-powered vehicles, regardless of whether those vehicles benefit the environment or the greater American economy.

How Expensive Is It to Generate and Distribute Hydrogen?

In the near-term, hydrogen fuel is likely to be more expensive than gasoline, and much more expensive if it is derived from renewable sources.

The National Academy of Sciences' draft 2004 study estimated that hydrogen costing $2.12 per kilogram would provide travel at about 3.3 cents per mile before taxes—about the same cost as driving a mile in a hybrid-electric vehicle fueled with gasoline. (A kilogram of hydrogen contains roughly the same amount of energy as a gallon of gasoline. The average pre-tax cost of gasoline in June 2004 was approximately $1.56 per gallon.[35])

Given current hydrogen technology (and assuming average fuel economy equal to the NAS's fuel-cell vehicle estimate of 65 miles per gasoline gallon equivalent), the NAS estimated that various options for producing and distributing hydrogen would cost the following—in order from least expensive to most expensive. (Estimates of the cost using future technology are listed in parentheses.)

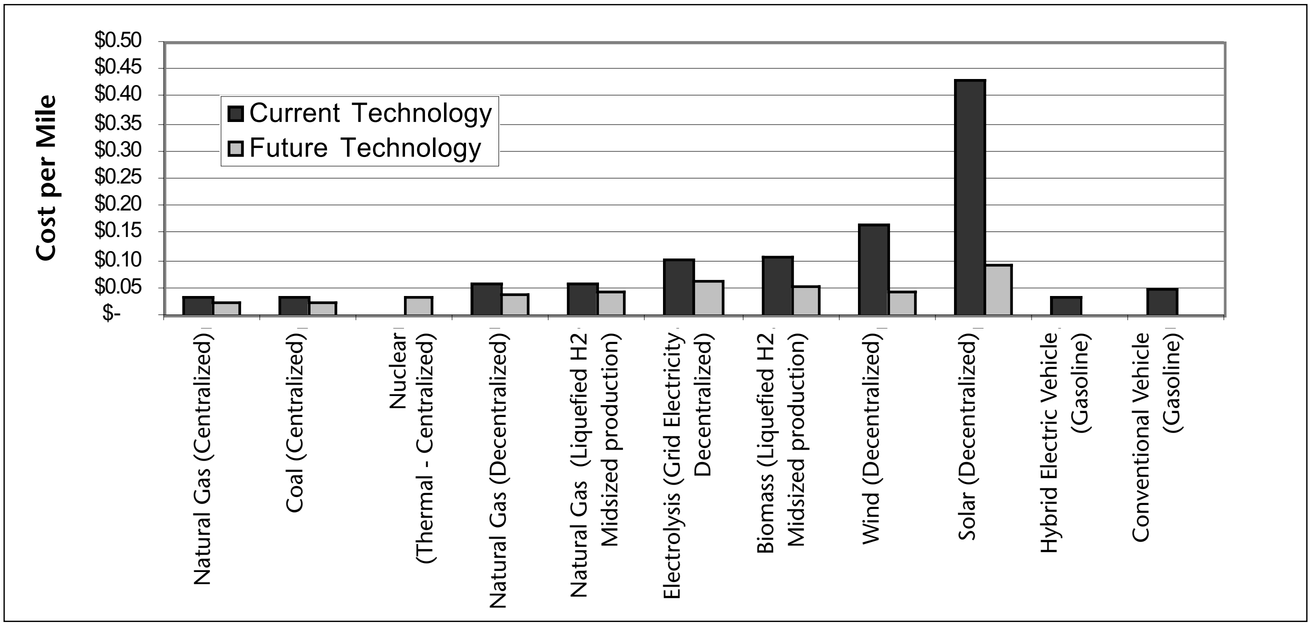
- Centralized production from natural gas, 3.3 cents/mile (2.7 cents/mile with future technology)
- Centralized production from coal, 3.3 cents/mile (2.6)
- Centralized production from nuclear (thermal), no near-term estimate (3.6)
- Decentralized production from natural gas, 5.7 cents/mile (4.3)
- Mid-sized production of liquefied hydrogen from natural gas, 6.0 cents/mile (4.2)
- Decentralized production from electrolysis, mix of grid and wind electricity, 10.5 cents/mile (5.4)
- Decentralized production from electrolysis, grid electricity, 10.5 cents/mile (6.4)
- Mid-sized production of liquefied hydrogen from biomass, 10.9 cents/mile (5.6)
- Decentralized production from wind, 16.5 cents/mile (4.4)
- Decentralized production from solar, 43.4 cents/mile (9.5)[36]

At first blush, it appears that centralized production from natural gas or coal is cost-competitive with gasoline right now. However, the NAS estimates assume that these centralized facilities—which would produce enough hydrogen for 2 million fuel-cell vehicles—are fully utilized. If they are not fully utilized (as they certainly would not be during the beginning of any transition to hydrogen), the per-unit costs would be much higher.

Thus, the decentralized production of hydrogen using natural gas appears to be the only hydrogen production strategy that would be competitive in the near term with gasoline—and even then, fuel costs would likely be nearly twice as great per mile as for a highly efficient hybrid-electric vehicle.

Should oil prices increase dramatically, however, the economics begin to change. A doubling of gasoline prices would make hydrogen from natural gas directly cost competitive. However, this assumes that natural gas prices will remain constant and that there will be sufficient supplies of natural gas. Neither of these conditions should be taken for granted—indeed, natural gas prices already exceed the prices assumed in the NAS cost analysis.[38]

Fig. 4. Cost per Mile of Hydrogen Fuel under Various Production and Distribution Scenarios at Full Utilization[37]



The National Academy of Sciences Study and Renewable Hydrogen

The National Academy of Sciences study considered only limited options for the renewable production of hydrogen. It is likely that the NAS study missed several options for the renewable production of hydrogen that may be more cost-effective than those considered in the study.

The NAS study was particularly limited with regard to assessing the viability of hydrogen from biomass—considering only options that involve the use of liquid (as opposed to compressed) hydrogen. Because liquefaction of hydrogen is a very energy-intensive process, the result is the reduced energy efficiency and cost-effectiveness of biomass under the NAS scenarios.

Similarly, the NAS study assumed electricity costs of 6 cents per kilowatt-hour in the near term from the generation of electricity from wind at decentralized locations. Already, wind power is being generated in certain parts of the country for less than 5 cents per kilowatt-hour.

These shortcomings do not override the NAS conclusion that—with current technology—renewably generated hydrogen is not likely to be cost competitive with hydrogen generated from fossil fuels. They do suggest, however, that the NAS conclusions about renewable hydrogen may be overly pessimistic and that more research is needed to explore the various options for renewable production of hydrogen.

How Would a Shift to Hydrogen Impact America's Energy Security?

Shifting to a hydrogen-based transportation system would almost certainly reduce America's dependence on foreign oil. But a transition to what appears to be the most likely source of hydrogen in the near term—natural gas—could replace our dependence on foreign oil with a dependence on foreign gas. And while the use of renewable energy to generate hydrogen would improve energy security, hydrogen may not be the best way to take advantage of these resources in the near term.

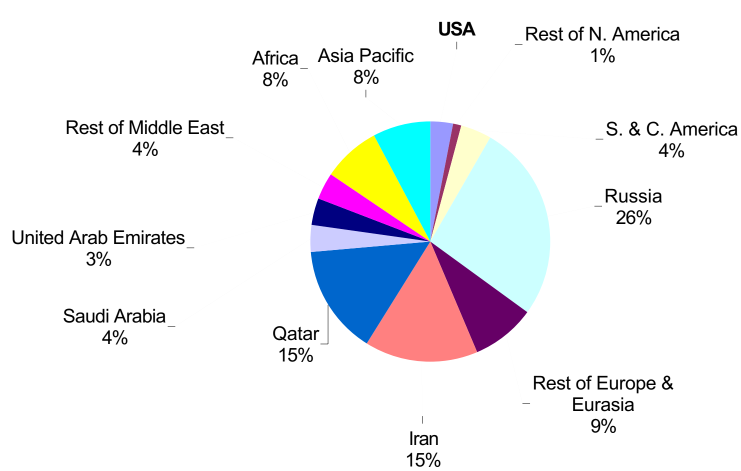
Natural Gas Supply Impacts

There is sharp disagreement about the degree to which a shift to a natural gas-based hydrogen economy would increase net consumption of natural gas in the U.S. Some suggest that by pairing the use of hydrogen in highly efficient fuel-cell vehicles with the use of stationary fuel cells in buildings and improvements in building energy efficiency, increases in natural gas consumption could be held to a minimum.[39] Assuming, however, that hydrogen is produced from natural gas using current technologies, data presented in the NAS study suggest that converting half of the nation's vehicles to operate on hydrogen would increase natural gas consumption by 16 to 22 percent compared to 2002 levels.[40]

Even if a natural gas-based hydrogen system results in only a marginal increase in gas consumption, the result could be increased importation of natural gas from overseas and/or price hikes that would have ripple effects throughout the economy. Federal Reserve Board Chairman Alan Greenspan, in 2003 congressional testimony, suggested that increased importation of natural gas is ***already*** necessary to hold the line on rising gas prices—even without a significant increase in demand from hydrogen-powered automobiles. The NAS study concluded that "if natural gas is used to produce hydrogen, and if, on the margin, natural gas is imported, there would be little if any reduction in total energy imports, because natural gas for hydrogen would displace petroleum for gasoline."[41]

Supporters of increased natural gas importation point out that world natural gas supplies are not as concentrated in the Middle East as are supplies of petroleum. While 63 percent of world petroleum reserves are concentrated in the Middle East, the region accounts for only 41 percent of proved natural gas reserves.[42]

Fig. 5. Share of Natural Gas Proved Reserves by Country/Region[43]



However, natural gas reserves—like petroleum reserves—are concentrated in a small number of countries. Five countries (Russia, Iran, Qatar, Saudi Arabia and United Arab Emirates) account for nearly two-thirds (64 percent) of the world's proved natural gas reserves—an even greater percentage than the share of the world's proved petroleum reserves controlled by the top five countries (Saudi Arabia, Iran, Iraq, United Arab Emirates and Kuwait). (See Fig. 5.)

Importation of natural gas also poses its own unique challenges. Liquefied natural gas (LNG) is both expensive to ship and extremely flammable, stoking fears that LNG tankers or terminals would be prime targets for a potential terrorist attack.

It is also important to remember that increased natural gas consumption in one sector of the economy can have ripple effects in other sectors as well. Recent increases in natural gas consumption in the electric industry, for example, have helped spark price spikes with serious impacts elsewhere in the economy, including agriculture, which relies on nitrogen-based fertilizers created using natural gas.[44] Should natural gas become a major source of hydrogen, pricing and consumption patterns in the residential and electric sectors could change significantly, with impacts on both the economy and the environment.

Renewable Options

Some believe that natural gas is best used as a bridge fuel to facilitate a transition to renewable hydrogen. Indeed, the "holy grail" from an energy independence and environmental point of view is the use of renewable sources of energy—such as solar, wind and biomass energy—to create hydrogen.

In the long run, a renewables-based hydrogen economy has enormous potential benefits. Hydrogen could provide a way to store the energy created by intermittent resources—such as solar and wind power—allowing them to play a greater role in the generation of electricity or the fueling of vehicles. Hydrogen could even be used to store solar or wind energy generated at homes and businesses.

Using solar and wind energy to power a fuel-cell vehicle includes two energy-losing steps—converting solar or wind electricity to hydrogen and converting the hydrogen back into electricity in a fuel cell.

In the short run, however, hydrogen generated from the wind or sun is unlikely to be cost competitive with hydrogen generated by fossil fuels. Achieving cost-competitiveness will require significant technological improvements as well as the achievement of volume production for technologies such as solar panels.

These technological improvements are more likely to be driven by a large-scale effort to expand the amount of solar and wind energy used to generate electricity than by a transition to a hydrogen-fueled transportation system. The reason is simple: using solar and wind energy to power a fuel-cell vehicle includes two energy-losing steps—converting solar or wind electricity to hydrogen and converting the hydrogen back into electricity in a fuel cell. These steps are not required when solar or wind energy provides power for the electric grid.

In some parts of the country, wind energy is cost-competitive with fossil fuel-fired electricity generation ***right now***. The price of wind power has been dropping for decades and state-of-the-art wind turbines in many parts of the country can generate power for less than 5 cents/kilowatt-hour—roughly competitive with new natural gas or coal-fired power plants.[45] Solar photovoltaic electricity remains much more expensive, but has the benefit of being a distributed resource, alleviating the need to build expensive new additions to the nation's electricity transmission system. Costs for solar power have also been decreasing quickly over the past several decades.

A hydrogen economy, therefore, will not necessarily develop into a renewable hydrogen economy. One of the most effective ways to ensure that hydrogen is eventually generated from renewable sources is to expand the deployment of wind and solar power to generate electricity today.

There is one renewable energy source that could play a substantial near-term role in the transportation system, either as a source of hydrogen or as a fuel itself: biomass. Biomass energy is already being used in vehicles that operate on ethanol or that use gasoline-ethanol blends designed to meet clean air standards. In addition to converting biomass into a liquid fuel, biomass can also be gasified to create hydrogen. Unlike other renewable energy sources, biomass does not need to go through the energy-intensive process of electrolysis to produce hydrogen, and thus may be more cost-effectively used as a replacement for fossil fuels in transportation than as a source of electricity.

Reliance on biomass energy poses a variety of environmental, social and economic questions that would need to be resolved prior to wide-scale adoption. But the potential benefits of biomass for energy security, its relative economic viability, and its potential global warming benefits merit strong consideration.

What Are the Major Economic Hurdles Facing Hydrogen?

Hydrogen faces a number of daunting economic hurdles. Hydrogen fuel-cell vehicles are very expensive and are likely to remain at least significantly more expensive than conventional vehicles for the foreseeable future. The fuel used to power those vehicles will likely be more expensive than gasoline—unless gasoline itself experiences a dramatic increase in price. And the capital investment needed to construct hydrogen fueling infrastructure is likely to be very significant.

To succeed in the marketplace, both hydrogen-fueled vehicles and hydrogen itself must come down in price dramatically. In addition, those who purchase hydrogen-fueled vehicles must have convenient places to refuel them.

Hydrogen-powered and other alternative fuel vehicles suffer from a "chicken and egg" problem: that is, that consumers are unwilling to buy hydrogen-fueled vehicles if there is no place to refuel them, and entrepreneurs are unwilling to invest in refueling infrastructure if consumers aren't buying hydrogen-fueled cars.

Breaking this stalemate will require either a technological fix or the intervention of government or industry to provide financing that encourages entrepreneurs to go "out on a limb" to build fueling stations. One technological fix that has been proposed by some advocates of hydrogen is to link hydrogen fueling with the use of stationary fuel cells in businesses. Natural gas reformers located in buildings could produce and store excess hydrogen that could

> Researchers with the Argonne National Laboratory have estimated that the cost of hydrogen infrastructure to support 40 percent of the light-duty vehicle fleet could be as much as $500 billion.

be used to fuel vehicles.[46] Because stationary fuel cells are more likely to be cost-competitive in the near future (due to their increased overall efficiency and possible benefits as a distributed source of electricity), this piggy-backing arrangement could reduce the cost of hydrogen fueling for businesses.

Should such a strategy prove unworkable, hydrogen fueling stations would likely require infrastructure similar to today's network of gasoline filling stations. The size of the capital investment that would be needed to create such an infrastructure is immense. Researchers with the Argonne National Laboratory have estimated that the cost of hydrogen infrastructure to support 40 percent of the light-duty vehicle fleet could be as much as $500 billion.[47]

Ultimately, however, government may be called upon to provide incentives to encourage the development of a hydrogen economy. Already, states such as California have discussed spending state money to construct hydrogen filling stations, and infrastructure issues are likely to be among the first major issues policy-makers face as hydrogen-fueled vehicles near commercialization.

Hydrogen and the Environment

Is Hydrogen Good for the Environment?

Fuel-cell vehicles operating on hydrogen release only heat and water—a big improvement over the toxic and smog-forming emissions released by gasoline-powered vehicles. Hydrogen internal combustion engine vehicles are nearly as clean. Clearly, for those who live in urban areas, where automobile air pollution is a major health problem, fuel-cell vehicles would be very beneficial.

But tailpipe emissions are only one of many environmental impacts from the production and use of motor fuels. To grasp fully the environmental impact of hydrogen, one has to look at the entire ***fuel cycle*** (in fossil fuel parlance, from "well to wheels").

Recall that hydrogen is not an energy source—like oil, coal or the wind—but rather an energy carrier, like electricity. In the same way that electricity can be created through either environmentally benign processes (such as solar power) or through extremely damaging processes (such as the extraction and combustion of coal), hydrogen can also be a "green" fuel or a dirty fuel, depending on its ***source***.

Further, hydrogen's environmental impact depends on the ***efficiency*** with which it is produced, distributed and used. The same is true of gasoline. The environmental impacts of gasoline would be much reduced if vehicles achieved higher mileage and required less fuel.

Third, hydrogen's environmental impact can only be assessed if we look at the ***potential alternatives***. Finally, we can only really judge hydrogen's environmental impact if we isolate the environmental problems hydrogen is intended to solve. Let's step back for a moment and review why we need ultra-low and zero emission vehicles in the first place.

What Environmental Problems Is Hydrogen Intended to Solve?

The environmental impacts of the use of petroleum in motor vehicles are numerous and widespread.

Vehicles are responsible for a large portion of the health-threatening air pollution that makes the air in many American metropolitan areas unsafe to breathe. In 2001, on-road motor vehicles were responsible for 37 percent of all U.S. emissions of nitrogen oxides (which contribute to urban smog); 27 percent of all emissions of volatile organic compounds (VOCs, which contribute to smog and contain many substances that are toxic to humans); and 29 percent of all emissions of small particulates (which have been linked to premature death).[48] Even these figures understate the problem, since vehicles are responsible for a larger share of emissions in many urban areas, where most Americans live.

Motor vehicles' contribution to global warming is equally significant and has even graver long-term consequences. In 1999, transportation was responsible for one-third of all energy-related emissions of carbon dioxide—the leading global warming gas—in the U.S., with the majority of transportation sector emissions coming from cars and trucks.[49] In fact, carbon dioxide emissions from transportation in the U.S. were greater than the total greenhouse gas emissions of any other country in the world, save China and possibly Russia.[50]

Finally, looking at the entire fuel cycle would reveal environmental damage caused by the extraction, production and distribution of petroleum. Oil spills, the degradation of land used for petroleum extraction, and the leakage of petroleum products into groundwater are among the many costly environmental impacts of these activities.

These three sets of problems all arise from the consumption of fossil fuels, but the solutions to those problems are not necessarily the same.

Emissions of health-threatening pollutants can be reduced in one of three ways: by using cleaner-burning fuels, reducing driving, or installing advanced emission controls. As a result of emission control regulations and the use of cleaner-burning gasoline, per-mile emissions of smog-forming nitrogen oxides (NOx) from new cars have been reduced by about 90 percent below levels that prevailed in the mid-1960s.[51] In addition, many models of vehicles currently on sale in California and selected other states emit levels of NOx that are approximately 90 percent below today's average cars.[52]

By contrast, no control device for automobiles currently exists that will reduce emissions of carbon dioxide—the key global warming gas—although some vehicular greenhouse gas emissions (e.g., nitrous oxide and methane) can be reduced through emissions controls and technology adjustments (e.g., changing refrigerants for automotive air conditioners). Similarly, while there are ways to mitigate the environmental impact of petroleum extraction, production and distribution, the only way to significantly reduce those risks is by reducing the consumption of petroleum products and avoiding the temptation to replace them with fuels that cause similar or greater environmental risks.

How Can Hydrogen Benefit the Environment?

Hydrogen can benefit the environment if:

- It reduces health-threatening air pollutant emissions.
- It reduces global warming emissions over the entire fuel cycle.
- It does not itself cause any additional serious environmental harm.

Most sources of hydrogen succeed in reducing health-threatening air pollutant emissions—particularly in urban areas. There are, however, other technologies that can achieve similar pollution reductions, some at relatively little expense. Vehicles certified to California's Partial Zero Emission Vehicle (PZEV) standards, for example, release about one-tenth the smog forming pollution of today's average vehicles—which are themselves dramatically cleaner than vehicles sold just a decade ago. Moreover, these vehicles are being sold at little to no cost premium to consumers—as opposed to the large cost premiums that are likely to accompany fuel-cell vehicles.[53]

With regard to global warming and other environmental impacts, the impacts depend on the sources of energy used to create the hydrogen and the efficiency with which it is used. Any evaluation of a new technology is very uncertain. For the following analysis, we primarily rely on two government sources—the National Academy of Sciences (NAS) and the Argonne National Laboratory (ANL)—that have compiled draft reports on the environmental impacts of various hydrogen and fuel cell technologies.[54] It is likely that these judgments will need to be revised over time to reflect the evolution of technology.

Hydrogen from Renewables

Hydrogen generated using electrolysis powered by renewable sources of energy—such as wind or solar power—is essentially emission-free. ANL's 2001 study found that the use of renewably generated hydrogen would slash greenhouse gas emissions per mile traveled by more than 90 percent, VOC emissions by more than 98 percent, and NOx emissions by 60 percent over the entire fuel cycle.[55]

However, there are alternative ways of using renewable energy that could produce greater reductions in emissions than using them to create hydrogen for vehicles. Assume that fuel-cell vehicles will primarily compete with hybrid-electric vehicles in the marketplace. Assume also that wind energy is harnessed to generate hydrogen at decentralized locations. Based on data from the NAS study, using current technologies, a kilowatt-hour of wind power used to generate hydrogen would provide enough fuel for a fuel-cell car to displace about 0.77 pounds of carbon dioxide emissions that would have resulted from using a hybrid vehicle instead. Using that same kilowatt-hour of wind power to displace power generation from the nation's electric grid, however, would yield approximately 1.2 pounds of carbon dioxide reductions.[56]

Thus, using wind power to displace existing sources of electricity generation would result in ***50 percent greater carbon***

Fig. 6. Carbon Dioxide Emissions from Fuel Cell Vehicles under Various Production and Distribution Scenarios[57]

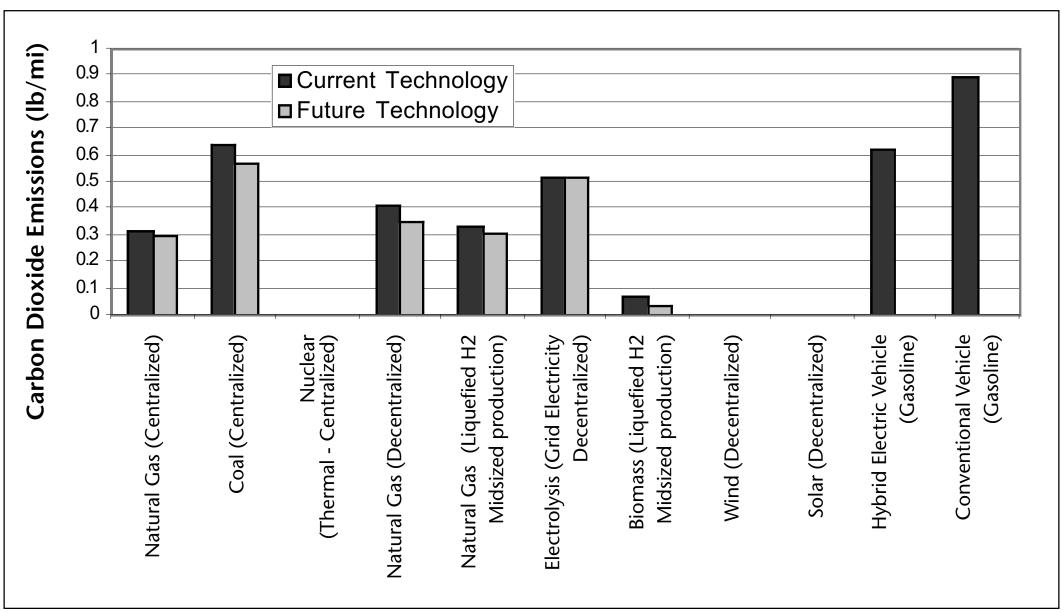
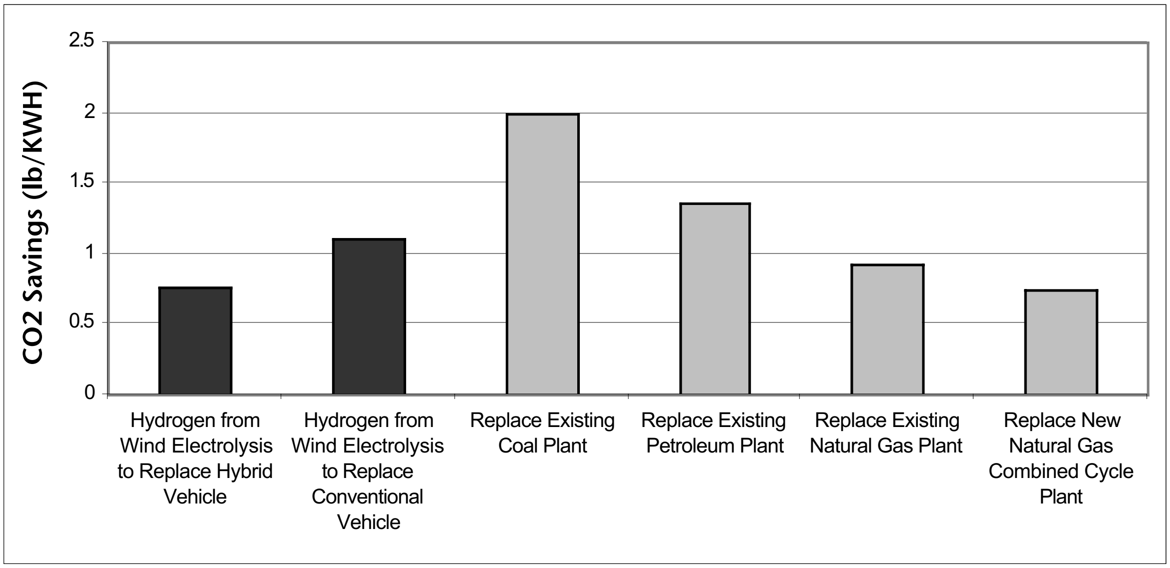


Fig. 7. Carbon Dioxide Emission Reductions per Kilowatt-Hour of Wind Power[58]



dioxide reductions than using that same wind power to displace travel in hybrid-electric vehicles. Indeed, the use of wind power to displace travel in hybrid-electric vehicles would provide only modest greenhouse gas reductions compared to displacing the most efficient form of fossil fuel-fired generation: modern natural gas combined cycle power plants. (See Fig. 7.)

Hydrogen from Biomass

Biomass energy (fuel from plants, plant wastes and animal wastes) is also renewable, but deserves special attention. Plants absorb carbon dioxide from the atmosphere as they grow. Thus, even though the burning of biomass releases carbon dioxide to the atmosphere, the use of biomass results in no net increase in carbon dioxide concentrations, assuming that new plants take the place of those harvested for energy use.

There are several ways to generate hydrogen from biomass. One is to refine the biomass into a liquid fuel—such as ethanol—which can then be converted into hydrogen. A benefit of this strategy is that ethanol can be distributed using a similar distribution network as is used to distribute gasoline today, and can even be used directly in vehicles that are not equipped with fuel cells. A second strategy is to produce hydrogen directly from biomass through gasification.

The ANL and NAS studies each took different approaches to the use of biomass. ANL modeled the impacts of ethanol reformed into hydrogen on board a fuel-cell vehicle. (***On-board reformation***—in which hydrogen is produced from fuel on board the vehicle—was once considered a leading option for fuel-cell vehicles but has since fallen into disfavor due to cost and engineering concerns.) Depending on the source of ethanol (corn versus cellulosic ethanol from agricultural waste products), the reduction in greenhouse gas emissions versus conventional gasoline vehicles range from 60 percent to more than 100 percent, meaning that the consumption of ethanol could result in ***negative*** net greenhouse gas emissions over the entire fuel cycle. The results for other air pollutants were less positive: consumption of ethanol in this manner would lead to increased per-mile emissions of NOx and particulates over the entire fuel cycle.

The NAS study reviewed the greenhouse gas impact of gasifying biomass for use in producing liquid hydrogen at mid-sized production facilities. On a per-mile basis, biomass fuel would release less than one-eighth the carbon dioxide as a hybrid electric vehicle operating on gasoline.[59] The NAS did not examine the emission of health-threatening pollutants from biomass gasification.

Unfortunately, both studies evaluated only very limited scenarios for the use of biomass in hydrogen production. Study of alternative scenarios—such as the reformation of ethanol at service stations or the centralized production of hydrogen gas from biomass—is needed to round out the picture.

We do know, however, that biomass fuels represent a potentially potent way to reduce global warming gas emissions, and that care must be taken to ensure that emissions of harmful pollutants do not increase in any biomass-hydrogen scenario.

The use of biomass raises a series of other environmental and social issues that are qualitatively different from those raised by other fuel options. On one hand, the use of biomass for fuel could provide a productive use for agricultural wastes while stimulating rural economies. However, in order for biomass to provide a major portion of the nation's energy, it is likely that new agricultural production of biomass will be required. The NAS report estimates that, if all of America's hydrogen were to be generated from biomass by 2050, it would require the use of approximately 33 percent of the nation's current cropland or 16 percent of rangeland and grassland.[60] Should this production require the intensive use of chemical pesticides or fertilizers, encourage the development of genetically engineered plants with uncertain effects on the environment, or displace land needed to raise food to feed a growing population—it could result in negative environmental or social consequences.

Hydrogen from Natural Gas

The use of natural gas to create hydrogen may have some environmental benefits in the form of reduced air pollution. The ANL study estimated that fuel-cell vehicles using compressed hydrogen generated from natural gas at decentralized facilities would create approximately 47 percent fewer emissions of greenhouse gases per mile than conventional vehicles. The NAS study estimated carbon dioxide emission reductions of about 30 to 50 percent below those of hybrid-electric vehicles running on gasoline.

For other emissions, the ANL study found that hydrogen from natural gas (generated and distributed as described above) would result in only very small emissions of VOCs, and per-mile NOx emissions 47 percent below those of conventional gasoline vehicles.

Because of natural gas' likely status as the main initial source of hydrogen for fuel-cell vehicles, both the ANL and NAS studies reviewed several scenarios for natural gas use in hydrogen production, shedding light on the impact that various infrastructure choices may have on the efficiency with which hydrogen is produced.

The NAS study, for example, found that the large-scale, centralized production of hydrogen from natural gas would produce significantly lower emissions of carbon dioxide than decentralized production at filling stations. The ANL study found little difference in greenhouse gas emissions between the two production methods, but did find that liquefaction of hydrogen from natural gas (as opposed to compression) reduced the greenhouse gas benefits considerably, due to the increased amount of energy required to liquefy hydrogen.

Natural gas, however, is not without environmental problems. The production of natural gas is far from environmentally benign, as natural gas drilling tends to fragment natural habitats and produces large quantities of saline water that can degrade the quality of waterways or groundwater resources if improperly managed.[61]

Questions surrounding the future availability and price of natural gas may also have environmental impacts. Should the need to use natural gas to manufacture hydrogen use supplies that are currently being counted upon to produce low-emission electricity, it is possible that other, less-expensive energy sources will come to replace natural gas in power generation. Those energy sources could be those with lower environmental impacts (such as wind) or greater environmental impacts (such as coal).

Hydrogen from Water Using Grid Electricity

Some have suggested the use of electricity from the nation's electric grid to create hydrogen through electrolysis. This is often thought of as a transitional strategy, allowing for the installation of numerous small-scale electrolyzers at filling stations in the years before centralized production of hydrogen becomes economically feasible.

Unfortunately, such a strategy appears to have few environmental benefits and may even cause significant harm. The ANL study estimated that such a strategy would result in significantly greater overall emissions of greenhouse gases, NOx and particulates, while the NAS study found that electrolysis from grid electricity would be no better in carbon dioxide emission terms than hybrid electric vehicles.

Electrolysis using grid electricity may be a worthwhile strategy if the electric grid itself becomes significantly cleaner through the replacement of polluting coal and oil-fired power plants with cleaner, renewable sources of energy. In the short run, though, such a strategy has little environmental merit.

Even here, however, the availability of potential alternatives looms large, since there is a strategy that can effectively use grid electricity to power vehicles while producing net environmental benefits. That strategy involves using grid electricity to directly power vehicles—either through the use of battery-electric vehicles or, more likely, plug-in hybrids. ***Plug-in hybrids*** are akin to regular hybrid-electric vehicles in that they partially recharge their batteries through regenerative braking and carry a gasoline-powered engine. Plug-in hybrids, however, also carry a significantly larger battery that can be used to store power from the electric grid—allowing the vehicle to travel short distances on electric power alone and reducing the gasoline engine primarily to the role of a "range extender." This eliminates one of the primary drawbacks of full battery-electric vehicles, the need for significant amounts of vehicle down-time for the recharging of batteries.

The ANL analysis showed that plug-in hybrids—using the same grid electricity as assumed above for electrolysis from hydrogen—would produce nearly 40 percent fewer greenhouse gas emissions per mile compared to conventional gasoline vehicles. The reason for these savings: increased efficiency. Using grid electricity directly in vehicles removes two energy-consuming steps from the hydrogen-from-electrolysis process: the generation of hydrogen from electricity and the conversion of hydrogen back into electricity in a fuel-cell vehicle.

Plug-in hybrids pose their own technological and cost challenges—particularly in the areas of battery storage capacity, vehicle weight, battery life-span, and battery cost. But given the similar challenges posed by fuel-cell vehicles and hydrogen production and storage, they deserve consideration and continued support.

Hydrogen from Coal

If there is a sure environmental loser as a source of hydrogen, it is coal. Coal is attractive as a source of hydrogen for two reasons: the United States has a lot of it, and it is relatively cheap. But widespread reliance on coal as a source of hydrogen would not help the environment, and in fact, would be a step backward.

The NAS study found that, on a per-mile basis, a fuel cell vehicle using hydrogen derived from gasification of coal would release at least as much carbon dioxide to the atmosphere as the combustion of gasoline in a hybrid electric vehicle. Gasification technology can reduce other harmful emissions as compared to conventional vehicles, as long as emission controls are in place to capture contaminants.

Those who support the use of coal as a source of hydrogen often point to the potential for ***carbon capture and storage*** (also known as sequestration)—in which carbon dioxide from coal combustion or gasification is captured and then stored either in underground rock formations or deep ocean waters. While carbon storage is technically possible (and has been employed in a few limited applications), it is as yet unproven—technologically, economically or environmentally—at the scale on which it would have to be employed to make a significant contribution to protecting the climate. The NAS report estimates that a hydrogen-powered transportation system relying on hydrogen generated from natural gas or coal would require the capture and storage of an immense amount of carbon—between 200 and 400 million metric tons each year.[62]

In addition, carbon storage has its share of unresolved potential environmental questions, including the degree to which stored carbon can be kept permanently out of the atmosphere, the effect on underground or marine biology, the effect on drinking water supplies, the risk of catastrophic releases of carbon dioxide that can asphyxiate humans or animals, and others.[63] These risks point to the need for far more study of carbon storage before it can be counted upon as a solution to coal's carbon dioxide problem.

However, the emissions from coal consumption are just the tip of the iceberg when it comes to the environmental impacts of coal. Water pollution and land degradation from coal mining are extremely severe problems that cannot be ignored. Increasing the production of coal to fuel vehicles—especially if there is no significant greenhouse gas benefit—is not environmentally justified.

Hydrogen from Nuclear Power

Hydrogen generated from nuclear power also has negative environmental and public safety ramifications. Among them:

- **Accident risk** – In the short history of nuclear power, the industry has experienced two major accidents—at Three Mile Island and Chernobyl—that endangered the health of millions of people. The Chernobyl accident alone contaminated an area stretching approximately 48,000 square miles, with a population of 7 million. Even today, 18 years after the accident, the region surrounding the reactor continues to suffer from highly elevated rates of thyroid and breast cancer and long-term damage to the environment and agriculture.[64]

  While the United States has thus far been spared an accident of the scale of Chernobyl, there have been numerous "near-misses." For example, in 2002, workers discovered a football-sized cavity in the reactor vessel head of the Davis-Besse nuclear reactor in Ohio. Left undetected, the problem could have eventually led to the leakage of coolant from around the reactor core.

  Accidents are not the only route by which people can be exposed to radiation from nuclear reactors. In fact, nuclear power plants release radioactive emissions as part of their routine operation.

- **Terrorism and sabotage** – The security record of nuclear power plants is far from reassuring. In tests at 11 nuclear reactors in 2000 and 2001, mock intruders were capable of disabling enough equipment to cause reactor damage at six plants.[65] A 2003 General Accounting Office report found significant weaknesses in the Nuclear Regulatory Commission's oversight of security at commercial nuclear reactors.[66]

- **Spent Fuel** – Nuclear power production results in the creation of tons of spent fuel, which must be stored either on-site or in a centralized repository. Both options pose safety problems. Centralized waste repositories require the transport of high-level nuclear waste across highways and rail lines within proximity of populated areas. Once the waste arrives, it must be held safely for tens of thousands of years without contaminating the environment or the public. And by the time America's controversial centralized nuclear waste storage facility at Yucca Mountain, Nevada opens (if it ever does) enough nuclear waste is likely to have already been created to fill the facility, making additional storage necessary.[67]

  On-site storage poses its own problems. Nearly all U.S. nuclear reactors store waste on site in water-filled pools at densities approaching those in reactor cores. Should coolant from the spent-fuel pools be lost, the fuel could ignite, spreading radioactive material across a large area. The cost of such a disaster, were it to occur, has been estimated at 54,000-143,000 deaths from cancer and evacuation costs of more than $100 billion.[68]

For these and other reasons (including the historically poor economics of nuclear power), nuclear energy should remain "off the table" as a solution to the environmental problems posed by vehicle travel.

The Importance of Efficiency

We have not yet directly addressed the issue of how hydrogen would be used in fuel-cell vehicles. Indeed, the benefits of hydrogen depend in large part on how efficiently it can be used to move people and goods from place to place.

The NAS study, for example, assumes that fuel-cell vehicles will eventually achieve the equivalent of 65 miles per gallon of gasoline. Early examples of fuel-cell vehicles have experienced a broad range in fuel economy. Honda's FCX has an EPA-rated fuel economy equivalent to roughly 50 miles per gallon of gasoline.[69] Toyota's FCHV has a fuel economy of about 64 miles per gasoline gallon equivalent.[70]

Improving the fuel economy of fuel-cell vehicles would dramatically improve the prospects for a viable and environmentally beneficial hydrogen economy, both by reducing the technical problems associated with the vehicles themselves (particularly the need for large hydrogen storage tanks) and in reducing the costs and environmental challenges resulting from production and distribution of hydrogen. Some supporters of a hydrogen economy, including the Rocky Mountain Institute, suggest that, with the adoption of lighter weight, more aerodynamic auto bodies and other advanced efficiency measures, fuel cells will make economic and technological sense in the very near future.[71]

The flip side is that these advances and others (such as the use of hybrid-electric

Unlike the hydrogen economy, however, improvements in efficiency for gasoline-based vehicles are clearly achievable right now.

drive) are available for conventional cars as well. The failure to implement these improvements has nothing to do with hydrogen, and everything to do with the economics of cheap gasoline and the profit motives of automakers. In other words, improving the efficiency of vehicles and their power trains makes both the hydrogen economy ***and*** the conventional gasoline-based economy less environmentally damaging. Unlike the hydrogen economy, however, improvements in efficiency for gasoline-based vehicles are clearly achievable right now.

Summary

The environmental impacts of a hydrogen economy depend greatly on the source of hydrogen. Deriving hydrogen from solar or wind power would be virtually emission-free, while deriving hydrogen from biomass is a potentially powerful strategy to reduce the global warming impacts of transportation (though it may create other environmental and social impacts).

Other potential sources of hydrogen—such as coal and nuclear power—are clearly too environmentally destructive to be considered attractive options. Proposals for the creation of hydrogen from "zero emission" coal depend on technologies—including gasification and carbon capture and storage—that are economically questionable and/or technologically unproven at the scale at which they would have to be developed to achieve the desired results. Unsolved problems with the disposal of nuclear waste, coupled with the risk of accidents, makes nuclear power a poor source of hydrogen.

Some potential sources of hydrogen are more ambiguous in their environmental impacts. Using natural gas to create hydrogen would reduce emissions of harmful air pollutants as well as emissions of global warming gases. The use of grid electricity to generate hydrogen now would likely have negative environmental impacts. But should the electric grid become cleaner in the years to come, it could provide a relatively clean source of hydrogen.

Other strategies, however, may reduce harmful air pollutant emissions and global warming emissions faster than a transition to hydrogen fuel in transportation—in some cases, while also making important contributions to the development of a truly clean, renewable hydrogen economy in the future. Using renewable power to replace dirty forms of electricity generation would likely produce greater global warming emission reductions at lower cost than using renewables to create hydrogen directly. At the same time, expansion of power generation from renewables would help create the economic and technological conditions needed for the economical use of solar or wind power to create hydrogen in the future. Efficiency improvements in today's vehicles, increasing the deployment of advanced hybrid-electric vehicles, and requiring the installation of advanced emission control technologies can achieve environmental benefits approaching those promised by hydrogen-powered vehicles operating on natural gas, while at the same time driving forward the same automotive technologies that will eventually be incorporated in hydrogen fuel-cell vehicles.

A Sustainable, Clean Transportation Strategy for the Future

America and the world face two interrelated energy challenges—the short-term challenge of how to make the best of our current technologies and the long-term challenge of developing the next generation of technologies and practices that will enable us to realize the dramatic reductions in fossil fuel use and global warming emissions needed to achieve sustainability.

Our response to the first challenge should be clear: We must use all available cost-effective tools to increase the efficiency with which we use energy and to reduce the environmental impacts of energy consumption. Unfortunately, a number of barriers—economic, political, institutional and behavioral—currently prevent us from taking full advantage of our short-term potential for energy efficiency and the use of non-polluting sources of energy. Thankfully, a series of public policy tools exist that can overcome those barriers. Implementing these policy changes should be the first priority of policy makers at every level of government.

An ancillary benefit of many of these short-term policy changes is that they help lay the technological groundwork for a sustainable hydrogen economy—if one develops. In order for a truly sustainable hydrogen economy to take shape, several critical technologies—including the electric-drive technologies in hybrid electric vehicles and various renewable energy technologies—must advance in parallel with hydrogen-specific technologies. Setting public policies that encourage these technologies is a win-win proposition, providing near-term benefits while removing obstacles in the path of a clean hydrogen economy.

The ideal response to the second challenge—the long-term energy challenge—is less obvious. It is clear that even a dramatic improvement in the fuel economy of cars and trucks would merely temporarily mitigate—rather than resolve—the energy security and environmental challenges posed by our reliance on petroleum. If we are to solve these problems for the long haul, the transportation system of the future must operate on fuels that are abundant and environmentally benign—in short, renewable fuels.

It is as a potential vehicle for the use of renewable energy sources in transportation that hydrogen fuel cells have their greatest value. Other sources of hydrogen—such as natural gas—may provide short-term environmental benefits or reduce our dependence on imported petroleum, but they do not solve the long-term sustainability problem that a hydrogen economy must address if it is to be worth the large investment likely to be required to make the transition.

Some suggest that fossil fuels such as natural gas could play an important role in the transition to a hydrogen economy. Employing natural gas in the short term, it is thought, would reduce the cost barriers facing hydrogen fuel, resolving the "chicken and egg" problem, and allowing fuel-cell vehicles to begin to make their way into commercialization.

The danger of such a strategy is that it does not inherently support the long-term goal of a renewable hydrogen economy. Indeed, there is no guarantee that hydrogen will come to be generated from renewable sources of energy in the future —particularly if government policy continues to emphasize the generation of hydrogen from coal and nuclear sources, as it has under the Bush administration.

To ensure that the long-term potential of hydrogen to free us from dependence on fossil fuels and other dangerous sources of energy is not squandered, renewable hydrogen must be emphasized in public policy from day one. Public funding and public policies should target the development of fuel-cell vehicle technologies, while not supporting hydrogen generation or infrastructure options that rely on fossil fuels.

Targeting public support to renewable hydrogen does not mean that non-renewable hydrogen options will not be developed. Sensible public policy might clear hurdles that stand in the way of non-renewable hydrogen options that promise short-term environmental benefits, such as the generation of hydrogen from natural gas, and allow private sector investment in those options. But public policy and investment should be geared toward achieving the long-term vision of a renewably powered transportation system.

Emphasizing the development of renewable hydrogen over the speedy deployment of hydrogen vehicles and infrastructure does have risks. Such a strategy could push back the introduction of fuel-cell vehicles (although this is much more likely to be determined by the pace of fuel-cell technology development and external factors, such as the availability and price of gasoline). However, a simultaneous emphasis on basic fuel-cell research and development—coupled with policies such as California's zero-emission vehicle requirement—will continue to serve as an incentive to move forward with hydrogen vehicle development.

To achieve these ends, while promoting approaches that can reduce fossil fuel use and pollution in the near term, we propose a three-part strategy for the future of our transportation system:

- Make today's cars cleaner and more efficient.
- Promote renewable energy.
- Lay the technological and policy groundwork for a renewably powered transportation system.

In addition, policy-makers should implement effective strategies to reduce the rate of growth of vehicle travel—thus reducing fuel consumption regardless of the type of fuel used to power cars and trucks.

1. Make Today's Cars Cleaner and More Efficient

Vehicle efficiency is a major factor in the future success of the hydrogen economy. The less hydrogen we need to power vehicles, the less infrastructure we will need to produce and distribute it, the easier it will be to surmount the fuel storage hurdle, and the more economical hydrogen-powered vehicles will be.

There are numerous opportunities to improve the cleanliness and efficiency of motor vehicles. Moreover, we can take advantage of many of these opportunities today by promoting the use of energy efficient and clean technologies on today's gasoline-powered vehicles.

The use of lighter-weight materials, increased use of hybrid-electric drive, improved transmissions, "drive by wire" technologies, and other technological advances can significantly improve the energy efficiency of today's vehicles and reduce their impact on the climate. A 2001 analysis by the American Council for an Energy-Efficient Economy found that improvements in automotive technology possible within the 2010-2015 timeframe could result in a 51 percent increase in average fuel economy over the entire new-car fleet at a minimal increase in cost.[72] A more conservative National Research Council analysis found that automakers could cost-effectively boost the fuel economy of their fleets by 12 to 42 percent.[73] A 2003 report by the Union of Concerned Scientists estimated that increased reliance on advanced hybrid technology could boost the fuel economy of the car and light truck fleet to an average of 60 miles per gallon.[74]

While fuel-cell vehicles have the potential for zero emissions of health-threatening pollutants, there are numerous near-zero emission vehicles available today. The California Air Resources Board (CARB) has certified 27 models of 2004 vehicles manufacturers to its Partial Zero Emission Vehicle (PZEV) standard—the toughest automobile emission standard in the world. CARB estimates that approximately 140,000 PZEVs will be on the road by the end of the year.

Emissions of smog-forming nitrogen oxides from PZEVs are 90 percent below emissions from today's average vehicles and emissions of volatile organic compounds are dramatically lower as well.[75] The additional cost of PZEVs has been estimated at $200 to $500, but the added costs have not typically been passed on to consumers.[76]

Unfortunately, with a few exceptions, automakers have generally not made PZEVs available outside of California and other states that have adopted California emission standards. Requiring the sale of PZEVs nationwide would dramatically reduce health-threatening emissions from vehicles.

Finally, it is very important that we develop specific strategies to promote the development of hybrid-electric vehicles. Technological improvements in hybrids can not only reduce fuel consumption in the short run, but can also make direct contributions toward the achievement of a hydrogen economy. First, some hybrids (such as the Toyota Prius) have the capability to drive the vehicle using only the electric motor. Fuel-cell vehicles will eventually also use electric motors. Thus, hybrids present the opportunity to experiment with and perfect the many electric drive technologies that will eventually be used in fuel-cell vehicles. Second, it is likely that at least the first generation of fuel-cell vehicles will include some form of hybrid system to enhance vehicle performance and improve efficiency. Improvements in hybrid drive will help bring that first generation of mass produced fuel-cell vehicles closer to reality.

(It is important to note that all hybrid-electric vehicles are not created equal, and that some proposed hybrid vehicle configurations provide only modest energy savings or environmental benefits. Public policy should be aimed at promoting energy-efficient, technologically advanced hybrids over those that fail to meet ambitious energy-saving or emissions criteria.)

Some suggest that the transition from conventional gasoline vehicles to hydrogen vehicles could be made not in a single leap, but in a series of gradual steps.[77] The first step is the transition to hybrid-electric vehicles, followed by the use of plug-in hybrids that draw power from the electric grid and use a small gasoline-powered engine to extend travel range. As fuel cells come onto the market, they replace the gasoline-powered engine, and eventually take on a larger role in propelling the vehicle.

Public policies that reduce auto emissions, improve automobile fuel economy, and encourage the deployment of hybrid vehicles, therefore, can not only provide a reasonably certain short-term "payoff" in reduced pollution and energy use, but can also lay the groundwork for a future transition to an all-hydrogen transportation system.

2. Develop Renewable Energy

One of the most important steps toward a clean, hydrogen-based transportation system is the rapid expansion of the generation of electricity from renewable sources.

On the surface, the use of wind or solar power to generate electricity might appear to have little to do with running cars on hydrogen. But for three reasons, expanding renewable power generation is necessary to ensure that a hydrogen economy is both environmentally responsible and economically viable.

First, distributed production of hydrogen using electrolysis is one of the leading candidates for hydrogen production in the early stages of a shift to a hydrogen-based transportation system. Yet, producing hydrogen from grid electricity—given the nation's current reliance on coal for electricity generation—would likely produce about as much greenhouse gas pollution as using gasoline to power our cars, as well as significant amounts of other pollutants, including radioactive waste from nuclear facilities. Replacing fossil fuel-fired power plants with clean, renewable sources of energy would reduce the environmental impacts of using grid electricity to produce hydrogen.

Second, if natural gas is primarily used to generate hydrogen, supply constraints would likely reduce the potential of natural gas-fired power plants to replace higher-polluting forms of electricity generation—and may even spark increased use of coal and oil in the electric sector. Increasing the use of renewables for electricity generation would provide a cleaner alternative to expanding the use of coal, petroleum or nuclear energy for electricity generation in the event that rising prices or supply disruptions make existing or future natural gas-fired power plants uneconomical.

Third, as the NAS report demonstrated, renewable generation of hydrogen is currently very costly. By increasing installations of wind turbines and solar power systems, industries that produce those technologies would achieve economies of scale that will lead to reduced costs—ultimately making a renewable hydrogen future much more easily attainable.

We must also remember that, for the time being, solar and wind power can make a more useful contribution in the fight against global warming if they are deployed to replace existing coal-fired generation of electricity, and not to generate hydrogen. That calculus could change in the future, but it will only likely change if we dramatically increase our use of renewable energy for the generation of electricity.

If we wish to achieve a clean hydrogen future, therefore, we need to generate much more electricity from renewable sources—regardless of whether we use it directly to create hydrogen for vehicles or to clean up our nation's electric grid.

3. Lay the Groundwork for a Renewable Transportation System

Improving the efficiency and cleanliness of motor vehicles and investing in renewable energy can generate major short-term payoffs in reducing our dependence on fossil fuels and hastening the development of a hydrogen economy. But there are also important opportunities both to remove important barriers that stand in the way of the hydrogen economy and to ensure that any transition to hydrogen is a clean and sustainable one.

The first major hurdles that must be removed are the technological hurdles that impede the development of hydrogen fuel-cell vehicles. We need to know how to make hydrogen-powered vehicles orders of magnitude cheaper than they are now, how to produce and distribute hydrogen fuel in the most energy-efficient and cost-efficient way possible, how to safely store sufficient amounts of hydrogen in vehicles, how to surmount the durability and cold-start problems of fuel-cell vehicles, and how to refuel hydrogen vehicles safely and inexpensively. Any one of these technological challenges—if left unresolved—could reduce the hydrogen economy's chances of ultimate success.

Hydrogen fuel-cell vehicles are not guaranteed to be beneficial to the environment or our energy security. But they hold sufficient potential to merit some public investment to support development of fuel cell technologies and the technologies that will be needed to enable the renewable generation of hydrogen.

Government can also act to remove other barriers to the deployment of hydrogen-powered and other zero-emission vehicles. Specifically, governments should move to develop and adopt codes and standards for the safe handling of hydrogen and other alternative fuels, terminate public subsidies for the petroleum industry to create a level playing field for new transportation options, and actively encourage the immediate deployment of fuel cells in applications in which they are cost-effective and improve environmental performance, such as in certain stationary applications.

The Need to Stabilize Growth in Vehicle Travel

The most direct way to reduce the consumption of fossil fuels for transportation is to reduce the growth in motor vehicle travel. Between 1970 and 2002, the number of miles traveled on American highways increased by more than 150 percent, from 1.1 trillion miles to 2.9 trillion miles, while the nation's population increased by only 42 percent.[78] This increase in travel is a major reason for the United States' continued dependence on foreign oil and our continued air quality problems—despite the dramatic improvements in vehicle fuel economy and per-mile emissions over the last three decades.

To illustrate the importance of vehicle travel reductions to a clean transportation future, consider the following scenario. Imagine that every car and truck in the U.S. today were instantly and magically to be replaced by one that emits only half the amount of carbon dioxide per mile—roughly the level of emission reductions we would expect from shifting from a gasoline-based transportation system to one dependent on hydrogen created from the distributed reformation of natural gas. Emissions would instantly decline, but then proceed to rise as vehicle travel increases over time. At the rate of increase in travel experienced in the U.S. over the last three decades, by 2027 emissions from vehicles would once again return to current levels.[79]

Even in a full hydrogen economy, it is likely that the production of hydrogen fuel will come with at least some environmental impact. If hydrogen is produced from coal or nuclear sources, the environmental impact would be immense; if it is produced from renewables, it would be dramatically reduced. Regardless, reducing the rate of growth of vehicle travel remains important to minimize the environmental impacts of transportation.

As with making today's vehicles cleaner and more efficient and promoting renewable power, reducing the rate of growth in vehicle travel is beneficial on its own terms—it reduces our dependence on foreign oil, limits traffic congestion, and reduces the need for expenditures on highway maintenance. As a result, policy-makers should make reducing vehicle-miles traveled a top priority alongside technological improvements in motor vehicles.

What Not To Do

Government has great potential to take positive actions that can lead us to a cleaner, more sustainable transportation system. However, government can also take actions that reduce the environmental benefits of a transition to a hydrogen-based transportation system. Thus, any public strategy on hydrogen must avoid certain pitfalls.

1. First, Do No Harm

Any strategy to promote hydrogen-fueled vehicles should begin with the premise that the resulting system would reduce our dependence on fossil fuels and have significantly less impact on the environment than the current, gasoline-based transportation system. Unfortunately, some of the investments in hydrogen research and development—particularly at the federal level—promote technologies with serious economic and environmental risks.

The Bush administration's hydrogen research strategy has been heavily tilted toward the production of hydrogen from coal and nuclear sources—both of which produce significant environmental damage. Spending on fossil fuel and nuclear hydrogen research has increased dramatically over the past several years, and now represents more than one-third of Department of Energy spending on hydrogen-related programs.[80]

Specifically, in 2003, the Bush administration inaugurated a 10-year, $1 billion project to build a "zero-emission" coal-fired power plant that would produce electricity and hydrogen, while capturing and sequestering carbon dioxide emissions.[81] Even if the program were to live up to its objectives (which is questionable, given the uncertainty over whether large-scale carbon sequestration will ever be proven feasible and environmentally sound), it would still fail to address the significant environmental problems posed by the extraction of coal. The federal government has also launched a Nuclear Hydrogen Initiative designed to demonstrate the production of hydrogen from nuclear reactors by 2017. Additional funds will be spent to reduce the cost of creating hydrogen from natural gas.

By contrast, the administration has proposed to spend just $375 million next fiscal year on the promotion of ***all*** renewable energy technologies—about half the amount dedicated to fossil fuel technologies.[82] Rather than increasing funding for core renewable technologies such as solar and wind power, federal funding—already minimal—has been held steady or reduced in the president's FY2005 budget.[83]

These investment priorities are at odds with a vision of a hydrogen future that is sustainable and environmentally friendly, and are likely to give a leg up to the dirtiest hydrogen technologies, rather than the cleanest. States and the federal government should adopt a "do no harm" strategy by devoting funds solely to hydrogen applications that hold the potential of moving us toward the renewable generation of hydrogen.

2. Don't Put All Our Eggs in One Basket

Hydrogen fuel-cell vehicles face numerous technological challenges before they can play a significant role in our transportation system. The presence of several dozen working fuel-cell vehicles on California's roads suggests that these challenges will eventually be overcome, but there are no guarantees.

As a result, it is important that we continue to develop all vehicle technologies with the potential to reduce our transportation system's dependence on fossil fuels and impact on the environment. Battery-electric vehicles, new variations on existing hybrid-electric vehicle designs, and vehicles that use renewable biofuels can each play a role in creating a sustainable transportation system for the future. Policy-makers should not lose sight of these technologies in the enthusiasm over hydrogen.

Similarly, it is important that we do not make too much of the wrong investments too soon—creating a series of sunk costs that either a) predispose the development of the hydrogen economy in a particular way, or b) must be written off at some point when we decide to take a new path.

For example, one of the central technical issues with regard to hydrogen fuel-cell vehicles—how hydrogen will be stored on board the vehicle—has yet to be resolved. Investing large amounts of taxpayer resources into the construction of filling stations that dispense gaseous hydrogen, for example, could prove to be a waste of money if automakers settle on another technology for storage. On the other hand, such an investment could predispose automakers to manufacture vehicles that can be refilled using gaseous hydrogen, even if it is not the best storage technology. In either case, investing too much, too early could prove dangerous.

The Bottom Line

Government policy toward the development of hydrogen should set as a primary goal reducing the nation's dependence on fossil fuels, both domestic and foreign, without shifting to energy sources with separate but equivalent risks, such as nuclear power. In the long term, this means encouraging the development of renewable sources of energy in every sector of the economy.

Achieving this goal in the transportation will require a balanced approach that not only supports ongoing research into hydrogen-fueled vehicles and other potentially beneficial technologies, but also improves the efficiency of today's vehicles, speeds the introduction of renewable energy technologies, and reduces the growth of vehicle travel.

Any hydrogen strategy that does not include progress in each of these areas—or that makes investments in hydrogen technologies known to have major, negative environmental impacts—does not help us achieve the goal of a clean transportation system.

Policy Issues Facing the States

State governments can make an important contribution toward reducing our dependence on fossil fuels for transportation and the consequences of that dependence for the environment and the economy. Below are some of the strategies states can adopt—or have already adopted—to bring the vision of a clean, sustainable transportation system within reach.

1. Making Today's Cars Cleaner and More Fuel Efficient

The federal government has the primary responsibility for developing and implementing automobile emission standards and fuel economy guidelines. But the Clean Air Act empowers states suffering from air quality problems to adopt California's more aggressive limits on automobile emissions. And states also have several non-regulatory opportunities to promote the purchase of more efficient vehicles.

California's Clean Car and Advanced Technology Vehicle Standards

Six northeastern states (Connecticut, Massachusetts, New Jersey, New York, Rhode Island and Vermont) have adopted, or will soon adopt California's stringent emission standards for cars and light trucks, known as the Low-Emission Vehicle II (LEV II) program. The LEV II rules are expected to reduce emissions of toxic air pollutants by about 23 percent below emission levels that would prevail under federal standards by 2020 and emissions of carbon dioxide from vehicles by 2.5 percent.[84]

A key facet of the LEV II program is the Zero-Emission Vehicle (ZEV) requirement, which encourages technological progress by requiring that a certain percentage of vehicles placed for sale within the state employ advanced automotive technologies. The ZEV program is credited with spurring a dramatic investment in electric vehicle technologies during the 1990s that led to the development of hybrids and has assisted in the development of fuel-cell vehicles.

The ZEV program sets sales requirements for three types of advanced-technology vehicles:

- Partial Zero-Emission Vehicles (PZEVs) are gasoline-powered vehicles required to emit virtually no smog-forming or toxic pollutants. Automakers are required to place the emission control systems of these vehicles under warranty for the entire useful life of the vehicles, ensuring that emissions do not increase over time. It is estimated that PZEVs will eventually make up about 30-40 percent of new car and light-truck sales in California under the ZEV program.[85]
- Advanced technology PZEVs (AT-PZEVs) meet the same emission standards as PZEVs, but must run either on an alternative fuel (such as hydrogen used in an internal combustion engine, natural gas or ethanol) or employ hybrid-electric drive. AT-PZEVs are expected to make up about 8 percent of new car sales under the program by 2012.
- Pure zero-emission vehicles (ZEVs)—such as hydrogen fuel cell vehicles—will be introduced in small numbers over the next decade, with thousands of such vehicles being delivered for sale per year beginning in 2013. The California Air Resources Board (CARB), which administers the program, is expected to convene a scientific advisory panel to consider whether the fuel cell production goals for model year 2009 and subsequent years are attainable.

Adoption of California's clean car and advanced technology vehicle standards can guarantee reduced emissions of health-threatening air pollutants in the near future, while also hastening the deployment of advanced vehicles that can provide the technological platform for a future shift to fuel-cell vehicles.

Vehicle Greenhouse Gas Standards

In 2002, California built upon its long history of pioneering efforts to clean up automobiles by enacting a law directing the state to set standards for greenhouse gas emissions from automobiles. The law calls for the development of limits that "achieve the maximum feasible and cost effective reduction of greenhouse gas emissions from motor vehicles." Limits on vehicle travel, new gasoline or vehicle taxes, or limitations on ownership of SUVs or other light trucks cannot be imposed to attain the new standards.[86]

The new limits will likely speed the introduction of technologies that can minimize greenhouse gas emissions from conventional vehicles—such as six-speed automatic transmissions, integrated starter-generators, improved air conditioners, and low-rolling resistance tires.[87] Many of these improvements have the side benefits of reducing operating costs and hastening technological changes that can support the development of fuel cell vehicles.

California is scheduled to enact rules for the carbon dioxide limits by January 1, 2006. The limits will go into effect for the 2009 model year. States can express a commitment now to adopt the limits once they are enacted, and begin to move toward enactment themselves next year. By doing so, states can reduce the climate impacts of today's vehicles, while also saving money and promoting the use of advanced automotive technologies.

Incentives and Disincentives

There are a variety of ways in which states can use tax and other incentives to encourage the use of cleaner, more efficient vehicles.

- **Alternative fuel tax incentives** – A number of states have enacted tax incentives to encourage the use of "alternative fuel" vehicles—those that operate on fuels other than gasoline.

These tax incentives include: tax credits for the purchase of alternative fuel vehicles or infrastructure, including fueling stations; exemptions from fuel sales taxes for the purchase of alternative fuels; rebates or loans toward the conversion of vehicles to run on alternative fuels or the construction of alternative fuel infrastructure; and exemptions from registration fees.

The definition of "alternative fuel" and "alternative fuel vehicles" in these laws is often quite broad, and may encourage the adoption of technologies with little benefit for the environment or energy security. For example, Arizona adopted a poorly designed tax credit program under which the state paid for up to 50 percent of the cost of purchasing a vehicle capable of burning an alternative fuel—including "bi-fuel" vehicles that can also operate on gasoline. The program blew a half-billion dollar hole in the state's budget, as car buyers rushed to purchase expensive gasoline vehicles and outfit them with small alternative-fuel tanks, which were rarely used.[88]

To achieve positive results, tax incentives for alternative fuel vehicles should clearly be tied to the use of alternative fuels, preferably by limiting incentives to only dedicated (single-fuel) vehicles that can make a significant contribution to reducing air pollution or global warming emissions.

- **Hybrid vehicle tax incentives** – A few states also extend rebates, tax credits or tax deductions to purchasers of hybrid-electric vehicles. The federal government also offers a tax deduction to hybrid vehicle purchasers, which is scheduled to phase out in 2006. Again, including a proper definition of "hybrid" is critical to ensuring that such an incentive yields positive results. Hybrid incentives should be limited only to vehicles that provide a significant efficiency and/or environmental advantage over conventional vehicles.
- **Feebates** – Several states have discussed the possibility of designing a schedule of fees and rebates that would vary based on either fuel economy or carbon dioxide emissions. The idea behind "feebates" is that car buyers purchasing less-efficient or higher-polluting vehicles would pay a fee, while those buying cleaner, more-efficient vehicles would receive a rebate. Feebate programs generally pay for themselves—that is, they generate no additional government revenue and do not require additional government expenditures. No state currently has a feebate system in place, but California, Maryland and several northeastern states are among those who have considered, or are considering, the adoption of feebates.
- **Motor fuel taxes** – Increased taxes on gasoline and other motor fuels provide an incentive for individuals to reduce their driving and to purchase more efficient vehicles. Academic research suggests that long-run fuel consumption is reduced by 3 to 10 percent for every 10 percent increase in fuel price. While motor fuel taxes have traditionally been unpopular with the public (and raise legitimate concerns with regard to their impact on low-income drivers), novel variations on the policy—such as the return of some or all of the additional revenue to taxpayers in offsets to other taxes—could reduce these concerns while retaining the incentive for the purchase of more fuel-efficient vehicles.
- **Non-financial incentives** – Several states allow drivers of hybrid-electric or alternative fuel vehicles to use high-occupancy vehicle lanes.

State Purchasing Requirements

A number of states have attempted to "lead by example" by requiring a percentage of state vehicle purchases to be alternative fuel or hybrid-electric vehicles. Other states have considered rules that would require the purchase of the most fuel-efficient vehicle available that would serve the specified governmental purpose, or would limit the purchase of sport utility vehicles to only those purposes for which they are truly needed. As is the case with other "alternative fuel" programs, many state purchasing programs have focused on the purchase of "bi-fuel" vehicles, which may never operate on the alternative fuel. However, state purchasing requirements could be refocused in such a way as to promote improved vehicle efficiency, the use of hybrid-electric drive, and eventually, the purchase of hydrogen fuel-cell vehicles.

2. Promoting Renewable Energy

A clean hydrogen economy for the future depends upon a dramatic expansion in our ability to harness the energy of the sun, wind and other renewable sources. Several states have taken strong action in recent years to increase the generation of renewable energy and promote research and development of renewable energy sources.

In some cases, states have classified fuel cells as "renewable" technologies worthy of direct state support. However, fuel cells only provide a renewable source of energy—and are worthy of state support through renewable energy programs—if the fuel used to power them is itself renewable. There are many other ways—such as through energy efficiency programs, utility incentives, and support for combined heat-and-power applications—that states can support the installation of non-renewable fuel cells.

Renewable Energy Standards

At least 14 states have adopted renewable energy standards (RESs, also known as renewable portfolio standards, or RPSs) that require that a certain portion of the electricity generated for sale in the state is derived from renewable energy. Generally, these standards require that a certain percentage of electricity be generated from renewable sources, with the percentage increasing over time. State renewable standards vary in several ways:

- **Percentage of renewables required** – Requirements range from about 2 percent of electricity from renewable sources to 30 percent (in Maine).
- **Requirements for new versus existing renewables** – The most aggressive state standards set a specific requirement for the development of "new" renewable resources, ensuring that production from renewables continues to grow over time.
- **Definition of "renewable"** – Some state renewable energy standards include very loose definitions of "renewable" resources, in some cases including combustion of municipal solid waste and certain cogeneration facilities as "renewable" resources. Several states provide more credit or set a minimum threshold for the generation of electricity from truly renewable resources such as solar or wind power.
- **Treatment of fuel cells and hydrogen** – States are split roughly evenly in whether fuel cells are counted toward renewable standard requirements. Among those states that do allow fuel cells to receive credit, states are again split as to whether they require fuel cells to run on "renewable" fuels.[89] Even then, there is some ambiguity as to whether hydrogen fuel cells count for renewable credit even if the hydrogen is derived from

non-renewable resources. Hawaii's standard is unusually specific in this regard, giving credit only to fuel cells using hydrogen derived from renewable sources.[90]

An appropriate state renewable standard would require the steady introduction of new renewable generation from clean sources, such as solar, wind, clean biomass and geothermal power—ideally with a target of increasing the percentage of renewably generated electricity sold by 1 percent per year. A strong renewable standard would also limit fuel cell credit to those fuel cells powered by hydrogen or other fuels derived entirely from renewable sources of energy. Again, the use of fuel cells that operate directly on fossil fuels or on hydrogen derived from fossil fuels may be environmentally beneficial, but state officials should find other ways to support these technologies that do not detract from the necessary expansion of clean renewable generation.

Renewable Energy Funds

In addition to renewable standards, at least 14 states now assess small charges on electricity bills to support programs to enhance the deployment of renewable energy. These state renewable energy programs have typically focused on supporting the installation of large-scale renewable energy projects, providing subsidies for consumers to install renewable energy in their homes and businesses, assisting in the marketing of renewable energy to consumers (such as through the sale of "green" electricity products), and building the infrastructure for renewable energy markets.[91]

Some renewable energy funds have directly assisted in the promotion of fuel cell demonstration projects. In keeping with the research, development and market preparation function of the funds, these efforts can be worthwhile even if the resulting fuel cells do not directly rely on renewable sources of energy—as long as the investment decisions are driven by the ultimate goal of generating hydrogen from renewable sources. However, renewable funds must also focus on a balanced mix of renewable energy options and devote significant amounts of resources on those technologies that are close to market readiness and those that best fit the renewable resource in a given area (for example, solar power in the Southwest or wind power in the Great Plains).

Tax Incentives

States have implemented a variety of tax incentives to encourage the production or installation of renewable or other clean energy sources in their states. Many of these programs also cover fuel cell installations.

Incentives include sales tax exemptions for the purchase of renewable energy equipment; corporate or personal income tax credits for the installation of renewable energy equipment; property tax exemptions; and exemptions from income tax on income derived from the sale or royalties on patents for clean energy technologies. Several states also offer production tax credits that provide a direct financial incentive to those who generate electricity using renewable resources.[92]

Interconnection Standards and Net Metering

A key issue for the development of small-scale renewable energy technologies—including stationary fuel cells—is the degree to which they can be connected to the electricity grid. Most consumers who install clean "distributed generation" technologies must remain connected to the electric grid to supplement their in-house generator or to protect themselves against long outages if their in-house generator fails. Utilities, however, have long discouraged the installation of distributed generation through their failure to respond to connection requests, high charges for "standby power" service and other disincentives.[93]

State and federal officials have recently begun to take action to make it easier for consumers to connect their distributed generation sources to the electric grid. The Federal Energy Regulatory Commission has proposed model interconnection standards for small distributed generation, and several states have worked to ease the interconnection process. In addition, 37 states have adopted rules that allow for "net metering"—in which consumers receive payment for the excess power they generate and sell back to the electric grid.

Interconnection standards and net metering are extremely important for the development of stationary fuel cells. While stationary fuel cells do not always use the same technology as transportation fuel cells, easing the installation of fuel cells in homes and businesses can assist in the development of fuel cell technologies generally, and may provide a basis for the integrated stationary-transportation hydrogen production mechanism advocated by the Rocky Mountain Institute and others as a starting point for a hydrogen-based transportation system.

3. Paving the Way for a Renewably Powered Transportation System

Thus far, we've discussed in detail several policy areas that do not directly deal with the use of hydrogen in motor vehicles. It is likely, however, that as progress is made toward the commercialization of hydrogen vehicles, states will increasingly be called upon to deal directly with issues of safety and infrastructure. Indeed, in some states, these issues are already beginning to arise.

Fuel Cell Partnership Programs

Several states have formed public-private partnerships to encourage the development and deployment of hydrogen-fueled vehicles. The largest of these is the California Fuel Cell Partnership, formed in 1999, which counts all six major automakers and numerous energy companies and fuel cell manufacturers as members.[94]

The goals of the partnership are:

- To facilitate the placement of more than 300 fuel cell cars and buses over the next several years.
- Promote fueling stations to support the vehicle fleets.
- Ensure "common-fit" fueling protocols.
- Prepare communities and train first responders for vehicles and fueling.
- Promote practical codes and standards.
- Enhance public awareness.
- Exchange information and resources worldwide.[95]

The California program's focus on pilot hydrogen and fuel cell projects is designed to provide real-world experience with the operation of fuel-cell vehicles and hydrogen fueling systems, which can then be used to improve the technology and document its feasibility.

While the California program has much promise, it is unlikely that many states can, or should, pursue programs of a similar scale. But more limited public-private partnerships—especially ones focused on basic research into fuel-cell vehicles and renewable hydrogen technologies—could prove beneficial. Michigan, for example, has created an incubator for alternative energy technologies and provided tax incentives for certified alternative energy businesses, enabling the state to piggy-back off its status as a center for automobile manufacturing.[96] New Mexico has launched an effort to explore a fuel-cell development and demonstration program that ties in with the hydrogen and fuel cell research being performed at the state's Sandia and Los Alamos national laboratories. Other states have created programs designed to take advantage of university research, the work of local fuel cell or hydrogen companies, programs supported by renewable energy funds, or a combination of all these efforts.[97]

Unfortunately, partnership programs come with significant risks. First, partnership programs can have the perverse effect of dampening competitiveness among various actors in the marketplace, resulting in less technological progress than would result if each of those competitors—motivated by the fear of falling behind in the development of a key technology—were to work separately.

Second, public funding can easily be channeled to the wrong recipients based either on flawed assumptions of how technology is developed or, occasionally, political influence. For example, partnership programs at the federal level have often provided substantial funding to major automakers rather than the smaller, more innovative companies that are more likely to invest substantially in research and

Partnership for a New Generation of Vehicles: A Case Study in Failure

The Partnership for a New Generation of Vehicles (PNGV) is an example of the potential problems that can arise from poorly thought-out public-private partnerships aimed at improving the environmental performance of motor vehicles.

PNGV was initiated by the Clinton Administration in 1993 as a partnership between the federal government and the three major U.S. automakers—Ford, General Motors and DaimlerChrysler. The program was designed to promote technological cooperation among the automakers to achieve the goal of developing an 80 miles-per-gallon production prototype vehicle by 2004. The federal government invested approximately $250 million annually into PNGV-related research.[99]

The plan for PNGV, however, did not require automakers to actually ***produce*** a vehicle incorporating new efficiency technologies—and, indeed, the average fuel economy of model 2003 vehicles sold or marketed by American automakers remains significantly lower than the fuel economy of vehicles sold by Japanese automakers such as Honda and Toyota.[100]

Moreover, as American automakers were working together on PNGV, both Toyota (1997) and Honda (1999), were introducing the first generation of highly efficient hybrid-electric vehicles—beating the American automakers to the market with hybrids by six years. Ironically, some credit the announcement of PNGV with encouraging Japanese automakers to undertake the research that resulted in the development of hybrid vehicles.[101]

In 2002, the Bush administration replaced PNGV with a similar FreedomCar partnership designed to promote fuel-cell vehicle development. However, FreedomCar retains many of the same problems that made PNGV an ineffective program.

development and undertake new technological approaches.[98] (See Partnership for a New Generation of Vehicles: A Case Study in Failure," page 50.)

Finally, partnership programs that carry the imprimatur of government provide an opportunity for automakers or others to deflect demands for short-term improvements in vehicle technology. Automakers, for example, used their participation in the federal Partnership for a New Generation of Vehicles to argue against improvements in federal fuel economy standards.

Not every state can (or should) become the "Silicon Valley" of hydrogen, but by using limited state funds to leverage connections between private and public players, partnership efforts can give a boost to basic fuel cell research—as long as any state funds are limited and narrowly targeted, and the programs are accountable to the public.

Should hydrogen prove to be a workable and beneficial fuel source, public-private efforts could become even more important in the opening stages of commercialization. Governments will need to work with a variety of private-sector actors to encourage them to take part in the ongoing transformation in a productive way. The U.S. Department of Energy's Clean Cities program, through which government officials and businesses work to expand the deployment of alternative-fuel vehicles, could serve as a foundation for those future efforts.

Infrastructure Programs

Government will eventually be called upon to play a role in resolving the "chicken and egg" problems posed by the need for hydrogen refueling facilities. The high cost of capital investment in hydrogen fueling stations means that incentives could be needed to encourage entrepreneurs to take the leap of faith necessary to install hydrogen fueling systems during the early stages of any hydrogen transition.

As noted earlier, many states have already created tax incentives and other financial rewards for businesses that construct alternative-fuel fueling stations for their own use or for the public. Other states, such as New York, have moved to provide access to alternative transportation fuels at toll road service areas and other state-owned facilities in order to expand access to the fuels. Similar efforts can encourage the development of hydrogen fueling infrastructure in the early stages of a transition to a hydrogen economy.

Some states are prepared to go farther. In California, Gov. Arnold Schwarzenegger has proposed a "Hydrogen Highway" program that would construct up to 200 hydrogen fueling stations along major highways in the state by 2010. The program is estimated to cost between $75 million and $200 million, with much of the investment coming from the private sector. However, the state would likely need to supply a significant amount of funding to the project, which could be raised through a bond issue or other means.[102]

Such a program could clear an important hurdle from the path of a transition to hydrogen fuel-cell vehicles. However, it is likely too soon for California—or any other state—to make an infrastructure investment of such magnitude.

First, key technological and logistical hurdles remain to be resolved before widespread introduction of fuel-cell vehicles can commence. Even the most optimistic automakers, such as General Motors, now predict that fuel-cell vehicles will not be available to consumers until around 2010. Indeed, even the question of how hydrogen would ideally be delivered to and stored within vehicles remains open to debate. Amid such uncertainty, it appears that any hydrogen-related investment of public funds should be targeted toward basic research into fuel-cell vehicles and into other initiatives to improve the fuel economy and environmental performance of vehicles and expand the use of renewable power.

Second, it must be remembered that natural gas-based hydrogen is not a long-term solution to either our energy security, environmental or global warming problems. It is hydrogen's potential to solve these problems that make it a worthwhile investment of public resources. Thus, it is imperative that public funds spent on hydrogen generation be directed primarily toward the generation of hydrogen from renewable sources of energy.

Details of the California proposal have not yet been made public, so it is too soon to evaluate it on the merits. If state officials are successful in leveraging significant amounts of private investment, matching or exceeding the investment of public funds, the initiative may prove to be worthwhile. Otherwise, the state should focus its funding and efforts on measures that improve the energy efficiency and environmental performance of vehicles in the short-run, while supporting renewable energy development that could pave the way for a truly renewable hydrogen economy.

Codes and Standards

Perhaps the first major issue states will need to grapple with in the transition to a hydrogen-based transportation system is the adoption of codes and standards for fuel cell vehicles and hydrogen fueling. As noted above, hydrogen poses unique safety issues that are much different than those posed by today's petroleum-based transportation system. Codes and standards will need to be developed that protect the public health and safety, but are not so onerous as to undermine the viability of hydrogen as a fuel.

The actual development of codes and standards for hydrogen use will likely take place at the national and international level. However, the adoption and enforcement of those codes and standards will take place at the state and local levels. State officials should monitor the ongoing development of standards and codes, and move quickly to adopt the most recent safety codes once they are promulgated. In addition, states should take the initiative to educate and train code enforcement officers on proper implementation of the codes, and to educate retailers and consumers about the specific safety practices made necessary by hydrogen fuel. By being aggressive in this area, states can remove one of the early potential barriers to the transition to a hydrogen-based transportation system and ease the introduction of fuel-cell vehicles to the marketplace.

Stationary Fuel Cells

Stationary fuel cells used to provide electricity for homes and businesses face fewer technological and economic challenges than fuel cells used in vehicles. A wider variety of fuel cell technologies is appropriate for stationary use, durability and the ability to start in cold weather are not major concerns, and the waste heat from the fuel cell can be used productively for space heating or water heating—boosting the energy efficiency of the overall system. In addition, stationary fuel cells provide a source of distributed generation of electricity, reducing the strain on the electric grid and adding to their economic value.

It is possible that stationary fuel cells will be technologically and economically competitive years before transportation fuel cells come into widespread use. Government policy should encourage the development and deployment of stationary fuel cells by reducing the barriers to interconnection with the electric grid and requiring distributed generation to be considered as an option in utility planning. By encouraging stationary fuel cell development, governments can help build a base of technological understanding and public acceptance that could later support a transition to hydrogen-powered vehicles.

Conclusion

The debate over the use of hydrogen as a transportation fuel has become increasingly heated. Hydrogen optimists and skeptics disagree strongly over the viability of hydrogen as a transportation fuel, the timeline for the introduction of fuel-cell vehicles, and the environmental and economic merits of a hydrogen-based transportation system. The ferocity of the debate, however, obscures several important issues.

First, public policy is unlikely to play a decisive role in determining whether and when a hydrogen economy will take shape. The pace of technological progress and the price of oil are just two among many factors that will influence the future timetable of a hydrogen economy. Time will bear out either the optimists or the skeptics, but as a society, we need to prepare for the eventuality that a hydrogen economy can succeed as well as for the possibility that it will fail.

Second, we must remember that the achievement of a hydrogen economy is not a worthwhile goal in and of itself. Rather, it is ***what hydrogen enables us to do*** that is important—namely, reduce our dependence on fossil fuels and the economic, environmental and public health impacts that come with that dependence. A hydrogen economy that serves this long-term goal is beneficial. If it does not serve this goal, it is a distraction. Public policy can play an important role in determining whether any future hydrogen economy helps to achieve economic and environmental sustainability by encouraging the right kinds of investments and setting high standards.

Finally, we cannot forget that the choice we face over our transportation future is not black-or-white. Both hydrogen optimists and hydrogen skeptics often suggest that we must choose between a hydrogen economy in the long run and progress toward a cleaner transportation system now. Nothing could be further from the truth. There are many policies—such as the promotion of hybrid-electric vehicles and expansion of renewable energy capacity—that not only provide short-term benefits to the environment and the economy, but also help us move closer to the realization of a clean hydrogen economy.

The path to a clean, renewably powered transportation system will be built on the foundation of these “win-win” policies.

Hydrogen and fuel cell technologies have tremendous transformative potential. We may not know the exact timetable for a transition to hydrogen, but it is not too soon to take the steps needed to push that transition—if it occurs—toward a sustainable result. Responsible governmental efforts are needed to promote research into hydrogen fuel-cell applications, develop small-scale hydrogen pilot programs, promote the development and use of renewable energy, and encourage the deployment of fuel cells in market niches where they make sense from an economic, environmental and energy security point of view (such as some stationary applications). It is also not too soon to lay the legal and regulatory groundwork for a transportation system that operates on hydrogen or other alternative technologies.

At the same time, however, there is substantial risk—both economically and environmentally—from proceeding too fast, too soon toward a hydrogen future that is, at present, ill-defined. The danger is especially acute given the federal government's current misguided tilting of the playing field in favor of nuclear and fossil fuel methods of generating hydrogen, and the economic pressures toward the short-term use of natural gas and electricity to generate hydrogen.

In pursuing a hydrogen economy, we must be clear that only the renewable generation of hydrogen will truly move us toward a transportation system that is non-polluting and adequately protective of the climate over the long haul. The short-term use of some fossil fuels—particularly natural gas—for hydrogen production may have some environmental and economic benefits, and government policy should not impede private-sector investments in that direction. But the goal of public policy and the investment of public funds should be targeted toward the development of the renewable sources of energy that can help us make the difficult transition to a clean, sustainable economy for the future.

The next few years will tell us a great deal about the viability of a future hydrogen economy. In the meantime, there is much that state officials can do to reduce the environmental and energy security threats posed by our dependence on fossil fuels for transportation. We do not need to "wait and see" before improving the fuel economy of vehicles, limiting vehicle emissions, taking advantage of our nation's abundant renewable resources, or providing cleaner, more efficient alternatives to automobile travel.

We have the tools to do each of these things ***right now***. And right now is the time to start.

Notes

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36. See note 17. Based on assumed mileage of 65 miles/kg H_2 for fuel-cell vehicles. These mileage estimates correspond with mileage levels postulated by the NAS committee for the car/light truck fleet in 2030; current mileage levels are lower, leading to increased cost per mile for all technology options. Taxes are not included in costs.

37. See note 17. Based on assumed mileage of 65 miles/kg H_2 for fuel-cell vehicles; 39 mpg for hybrid-electric vehicles and 27 mpg for conventional vehicles. These mileage estimates correspond with mileage levels postulated by the NAS committee for the car/light truck fleet in 2030; current mileage levels are lower, leading to increased cost per mile for all technology options. Taxes are not included in cost of gasoline or hydrogen.

38. The NAS study assumed natural gas prices of $4.50 per million BTU (industrial rate) for centralized hydrogen production and $6.50 per million BTU (commercial rate) for distributed production. Industrial natural gas prices in 2003 averaged approximately $5.60 per million BTU and commercial prices approximately $8.00 per million BTU. The U.S. Department of Energy projects that natural gas prices will remain high through 2005. Sources: U.S. Department of Energy, Energy Information Administration, *Monthly Energy Review April 2004*, 28 April 2004; U.S. Department of Energy, Energy Information Administration, *Short-Term Energy Outlook*, 7 July 2004.

39. See note 19.

40. The NAS scenario for centralized reformation of natural gas would require approximately 66.6 billion cubic feet of natural gas per year to service about 2 million fuel-cell vehicles, while the scenario for decentralized reformation at filling stations assumes consumption of about 37 million cubic feet of gas per year to service 854 vehicles. With approximately 230 million motor vehicles on the road, serving 50 percent of them would equate to an increase in natural gas consumption of about 16 percent of current consumption if the hydrogen is produced centrally and about 22 percent if it is produced at filling stations – not including any reductions in natural gas used in the production of petroleum. Consumption data from U.S. Department of Energy, Energy Information Administration, *Annual Energy Review 2002.*

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56. Assumptions based on NAS study: Power required to create 1 gasoline gallon equivalent (gge) of hydrogen (kg) using decentralized electrolysis of 52.49 kWh; hydrogen fuel-cell vehicles achieve 65 miles per gge; hybrid vehicles achieve 39 miles per gallon of gasoline; gasoline consumption produces 24.2 lb. of CO_2 emissions (well-to-wheels).

One mile of travel in fuel-cell vehicle thus requires 0.81 kWh of wind energy. (52.49 kWh/gge * 1 gge/65 mi.) One mile of travel in hybrid vehicle causes 0.62 lb. of CO_2 emissions. (24.2 lb. CO_2/gal * 1 gal./39 mi.). Thus, displacement of one mile of travel in hybrid by one mile of travel in fuel-cell vehicle = 0.62 lb. CO_2/mi. * 1 mi./0.81 kWh = 0.77 lb. CO_2 displaced per kilowatt-hour of wind energy. Carbon dioxide emissions from U.S. electric power sector based on EIA, *Emissions of Greenhouse Gases in the United States 2002*, October 2003 = 2,249

million metric tons carbon dioxide = 4.96 trillion pounds CO_2. Net generation of electric power in U.S. from EIA, *Annual Energy Review 2002*, October 2003, Table 8.2a = 3,839 billion kWh. Carbon dioxide emissions potentially avoided from 1 kWh of wind power replacing average grid power = 1.3 pounds. Assuming 10 percent transmission and distribution losses, displacement of CO_2 emissions equals approximately 1.2 pounds per kWh of wind energy.

57. See note 17. Based on assumed mileage of 65 miles/kg H_2 for fuel-cell vehicles; 39 mpg for hybrid-electric vehicles and 27 mpg for conventional vehicles. These mileage estimates correspond with mileage levels postulated by the NAS committee for the car/light truck fleet in 2030; current mileage levels are lower, leading to increased cost per mile for all technology options.

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78. Vehicle travel: U.S. Department of Transportation, Federal Highway Administration, *Highway Statistics 2002* and *Highway Statistics: Summary to 1995*. Population data: U.S. Census Bureau, "Population, Housing Units, Area Measurements and Density," *1990 Census of Population and Housing: 1990 Population and Housing Unit Counts: United States*, downloaded from www.census.gov/population/www/censusdata/hiscendata.html, 2 July 2004; U.S. Census Bureau, *Population Estimates: National Sex and Age: Annual Estimates of the Population by Sex and Five-Year Age Groups for the United States: April 1, 2000 to July 1, 2003*, downloaded from eire.census.gov/popest/data/national/tables/NC-EST2003-01.pdf, 2 July 2004.

79. Based on 3 percent annual growth rate in VMT from 1970 to 2002 from data cited in note 78. Doubling time at such a rate of growth would be approximately 23 years.

80. See note 17, Appendix C. Includes spending on both research directly related to hydrogen and "associated" research.

81. See note 16.

82. Union of Concerned Scientists, *President Bush's Fiscal Year 2005 Budget: New Priorities Needed*, downloaded from www.ucsusa.org/news/positions.cfm?newsID=380, 5 May 2004.

83. *Hydrogen and Fuel Cell Letter*, "DoE 2005 H2 Budget Request is $227 Million, Includes $95 Million for Core Program," February 2004.

84. Based on estimated emission reductions in Massachusetts, New York and Vermont under LEV II from Northeast States for Coordinated Air Use Management, Cambridge Systematics, *White Paper: Comparing the Emissions Reductions of the LEV II Program to the Tier 2 Program*, October 2003.

85. Based on estimated ZEV program production figures from California Environmental Protection Agency, Air Resources Board, *The 2003 Amendments to the California Zero Emission Vehicle Program Regulations: Final Statement of Reasons*, January 2004, 38, and estimated vehicle sales base from California Environmental Protection Agency, Air Resources Board, *Staff Report: Initial Statement of Reasons: 2003 Amendments to the California Zero Emission Vehicle Program Regulations*, 10 January 2003. There are many potential ways that manufacturers can comply with their ZEV program obligations. As a result, these figures are rough estimates.

86. California Assembly Bill 1493, adopted 29 July 2002.

87. California Environmental Protection Agency, Air Resources Board, *Draft Technology and Cost Assessment for Proposed Regulations to Reduce Vehicle Climate Change Emissions Pursuant to Assembly Bill 1493*, 1 April 2004.

88. Ross E. Malloy, "Costly Plan to Promote Alternative Fuels Jolts Arizona," *New York Times*, 2 November 2000.

89. See Database of State Incentives for Renewable Energy (DSIRE), accessed at www.dsireusa.org, 5 May 2004.

90. Hawaii Revised Statutes, Sec. 269-91.

91. Mark Bolinger and Ryan Wiser, Lawrence Berkeley National Laboratory, *Clean Energy Funds: An Overview of State Support for Renewable Energy*, April 2001.

92. See note 89

93. R. Brent Alderfer, M. Monika Eldridge, Thomas J. Starrs, National Renewable Energy Laboratory, *Making Connections: Case Studies of Interconnection Barriers and Their Impact on Distributed Power Projects*, July 2000.

94. California Fuel Cell Partnership, *Members*, downloaded from www.cafcp.org/about_members.html, 5 May 2004.

95. California Fuel Cell Partnership, *2004-2007 Goals*, downloaded from www.cafcp.org/about_goals.html, 5 May 2004.

96. See NextEnergy, www.nextenergy.org.

97. Mention of these or other programs in this report does not connote endorsement. The appropriateness of government subsidies to private business efforts depends on the goal of the program, the amount of money given, the results achieved, the assurance of public accountability, and the degree to which details about the programs are openly available to the public. We have not reviewed the programs mentioned here on any of these criteria, and we welcome further research on this topic.

98. In a 2000 paper on the Partnership for a New Generation of Vehicles, Daniel Sperling of the Institute of Transportation Studies at University of California, Davis notes that "[M]ost innovation for leapfrog transportation

technologies appears to come from outside the major automotive companies and even outside the traditional suppliers." See: Daniel Sperling, *Rethinking Private-Public R&D Partnerships: Lessons from PNGV*, 10 November 2000.

99. U.S. General Accounting Office, *Cooperative Research: Results of U.S.-Industry Partnership to Develop a New Generation of Vehicles*, March 2000.

100. U.S. Environmental Protection Agency, *Light-Duty Automotive Technology and Fuel Economy Trends: 1975 Through 2003*, April 2003.

101. See Jack Doyle, *Taken for a Ride: Detroit's Big Three and the Politics of Pollution*, Four Walls Eight Windows (New York), 2000,390.

102. State of California, *Governor Arnold Schwarzenegger's California Hydrogen Highway Network Action Plan*, downloaded from www.hydrogenhighway.ca.gov/vision/vision.pdf, 5 May 2004.

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