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The Hydrogen Economy and Its Potential Impacts

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I. Introduction

Air pollution emissions that prevent many areas of the country from achieving the Clean Air Act's (CAA's) national ambient air quality standards (NAAQS)[1] could be reduced if cleaner sources of energy were utilized. Clean energy supplied by domestic sources also could provide benefits to the overall environment,[2] the economy and to national security. President George W. Bush announced in his 2003 State of the Union Address that his Administration believes hydrogen fuel should help provide for the future energy needs of the United States.[3] The Administration and the U.S. Department of Energy (DOE) have declared their goal is to use hydrogen in vehicles by 2015[4] and to implement a "hydrogen economy," with the necessary infrastructure to make, transport, store, and use hydrogen as a fuel for fuel cell vehicles by 2020.[5] This will be a substantial challenge because in 2002, there were 518,919 alternative vehicles in use in the United States, but none used hydrogen.[6]

Hydrogen usually serves as an energy carrier that is derived from some other primary fuel. The existing infrastructure for petroleum-based fuels is unlikely to accommodate hydrogen fuel; a new infrastructure will take many years to build, and the effort will be expensive and politically difficult to accomplish. Without the necessary infrastructure, investors will be wary about supporting this technology. Moreover, the transport and storage of hydrogen is potentially dangerous; containment methods are prone to leak and present safety risks.

There are only limited cost-effective ways to use hydrogen to power automobiles or stationary internal combustion engines. The major focus of recent research has been on using hydrogen in a fuel cell, rather than using it as fuel in an internal combustion engine, but fuel cells have cost, consumer acceptance, durability, and other problems to overcome, as discussed below. At this time, it is not known how long it will take to overcome these obstacles in order to make the use of hydrogen fuel a reasonable choice. As Ex-

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[1] 42 U.S.C. §§7401-7671q, §7409, ELR Stat. CAA §§101-618, 40 C.F.R. pt. 50.

[2] The release of air pollutants such as sulfur dioxides (SO_2), nitric oxides and nitrogen oxides (NO_x) and heavy metals, for example, are significant sources of water pollution.

[3] The 2003 State of the Union Address: Complete Transcript of President Bush's Speech to Congress and the Nation (Jan. 28, 2003), *available at* http://www.whitehouse.org/news/2003/012803-sotu.asp (last visited Apr. 7, 2004).

[4] U.S. DOE, Draft, Multi-Year Research, Development, and Demonstration Plan, Executive Summary iii (2003), *available at* http://www.eere.gov/hydrogenandfuelcells/mypp/pdfs/exec_summary.pdf (last visited Apr. 9, 2004) [hereinafter Multi-Year Research Plan].

[5] Hydrogen Economy Fact Sheet: U.S.-EU Summit, Cooperation on the Development of a Hydrogen Economy (2003), *available at* http://www.whitehouse.gov/news/releases/2003/06/20030625-6.html (last visited May 11, 2004).

[6] Stacy C. Davis & Susan W. Diegel, Transportation Energy Data Book: Ed. 23, at 6-3, tbl. 6.1 (2003) [hereinafter Davis & Diegel]. *See also* tbls. 6.2, 6.3.

xon-Mobil Corporation's Manager of Fuels Development has stated: "The verdict is still out on whether hydrogen will ever become a mainstream fuel."[7]

II. Using Hydrogen as a Fuel

Hydrogen and other alternative fuels have become a subject of intense interest because of concerns about global warming, the fear that petroleum reserves may dwindle within a few decades, the potential disruption of petroleum supplies due to the instability of petroleum suppliers, and the desire to utilize fuels cleaner than fossil fuels to protect the environment. Hydrogen-based energy technologies are being pursued, in part, because of concerns about the need to reduce dependence on foreign oil in the United States.[8] However, even at maximum levels of hydrogen use, U.S. petroleum needs cannot be supplied by domestic sources because the public is not yet ready to take the steps necessary to significantly reduce the nation's oil dependence. The historical progression of the fuels used in the United States has been from wood to coal, to petroleum, to natural gas, and perhaps now to using hydrogen as an energy carrier.[9] These fuels represent a molecular progression with the ratio of hydrogen to carbon atoms increasing. This progression usually results in reduced air pollution and less carbon dioxide (CO_2) produced during the combustion process, but this is nullified by the increasing amount of fossil fuel that is combusted to meet the growing demand for energy.

A major benefit of using hydrogen as an energy carrier is that it can be produced from many energy sources. Coal, petroleum, and natural gas are the most readily available potential sources of hydrogen. Biomass also can be converted to hydrogen. A goal of scientists and DOE is to obtain hydrogen using biophotolysis or photofermentation,[10] but such technology is probably decades from development.

Hydrogen also can be produced using renewable sources of electricity or nuclear power to split water into hydrogen and oxygen. No CO_2 is formed when producing hydrogen through electrolysis of water using wind, solar, hydroelectric or nuclear fission, to generate the needed electric power, but some of these technologies are embryonic.[11] The technology to produce hydrogen from renewable or nuclear sources is currently high in cost and low in efficiency.[12] Some of the more potentially viable renewable means of producing hydrogen include hydroelectric water electrolysis and high-temperature thermochemical hydrogen production through solar heat.[13] Of the renewable technologies, the cheapest is biomass, rivaling coal in cost per million British thermal units (Btus), followed by electrolysis; the most expensive is solar photovoltaic electrolysis.[14] Wind-generated electricity is probably the least expensive way to produce hydrogen through electrolysis using renewable energy. Once the nation's infrastructure that is needed to store, deliver, and use hydrogen[15] is developed, and as technology improves hydrogen, production methods could be changed without an adverse effect on the hydrogen infrastructure.

The most common and efficient way of obtaining hydrogen today is steam reforming of natural gas,[16] but natural gas is less abundant than coal[17] and is not a renewable source. Coal is an abundant natural resource, but it creates substantial environmental problems when used in the hydrogen-formation process or when burned directly for energy. Even if hydrogen could be produced from coal with no release of conventional pollutants, little is gained from using hydrogen if the process results in releases of CO_2 to the environment. DOE plans to sequester and store CO_2 that is a byproduct of processing hydrocarbons to obtain hydrogen, but the technology to do this effectively on a large scale has not yet been proven.

Given the amount of energy it takes to produce hydrogen from other energy sources, it may be more efficient to use these energy sources directly rather than accepting the costs and inefficiencies in converting the hydrogen in fossil fuel to molecular hydrogen. However, the efficiency of a fuel cell in comparison to the internal combustion engine may help to mitigate the energy losses that occur during the conversion process used to produce hydrogen.

III. Overview of Hydrogen Technology

Currently, hydrogen is used primarily to make ammonia fertilizer by synthesizing ammonia (NH_3) and to hydrocrack petroleum in oil refineries in order to produce light gasoline and distillate fuel oil.[18] Hydrogen also is used in methanol production, metals processing, and in the electronics industry. Some businesses currently use stationary hydrogen-powered generators as back-up power; a few use hydrogen-fueled generators as their

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[7] Jeffrey Ball, *Green Dream: Hydrogen Fuel May Be Clean But Getting It Here Looks Messy—Auto Oil Companies Wrestle With Huge Costs to Build Delivery Infrastructure—Cautiously Topping the Tank*, WALL ST. J. (Eastern Ed.), Mar. 7, 2003, at A1.

[8] MULTI-YEAR RESEARCH PLAN, *supra* note 4, at I; U.S. DOE, DRAFT, MULTI-YEAR RESEARCH, DEVELOPMENT, AND DEMONSTRATION PLAN, PROGRAM BENEFITS 2-1 (2003), *available at* www.eere.energy.gov/hydrogenandfuelcells/mypp/pdfs/2.0_program_benefits.pdf (last visited May 11, 2004) [hereinafter MULTI-YEAR PROGRAM BENEFITS].

[9] Brian Cook, *An Introduction to Fuel Cells and Hydrogen Technology*, HELIOCENTRIS, Dec. 2001, at 2, *available at* www.FuelCellStore.com/products/heliocentris/INTRO.pdf (last visited May 11, 2004).

[10] Idaho National Engineering and Environmental Laboratory, *Biotechnology Processes for the Production of Hydrogen*, *at* http://energy.inel.gov/fossil/hydrogen/bioproduction.shtml (last visited Nov. 1, 2003). *See also* U.S. DOE, A NATIONAL VISION OF AMERICA'S TRANSITION TO A HYDROGEN ECONOMY—TO 2030 AND BEYOND iv (2002) [hereinafter NATIONAL VISION].

[11] MULTI-YEAR RESEARCH PLAN, *supra* note 4, at 3-5.

[12] NATIONAL VISION, *supra* note 10, at 4.

[13] MULTI-YEAR RESEARCH PLAN, *supra* note 4, at 3-5.

[14] JAMES J. MACKENZIE, THE KEYS TO THE CAR: ELECTRIC AND HYDROGEN VEHICLES FOR THE 21ST CENTURY 67 (World Resources Institute 1994) [hereinafter THE KEYS TO THE CAR].

[15] Venki Raman, *The Hydrogen Fuel Infrastructure for Fuel Cell Vehicles*, *in* CHALLENGES FOR THE CHEMICAL SCIENCES IN THE 21ST CENTURY: ENERGY AND TRANSPORTATION 66 (2003) [hereinafter *The Hydrogen Fuel Infrastructure*].

[16] NATIONAL VISION, *supra* note 10, at 4.

[17] *Future Options for Generation of Electricity From Coal: Hearings Before the Subcomm. on Energy and Air Quality of the House Comm. on Energy and Commerce*, 108th Cong. 10 (2003) (prepared statement of Hon. Ralph M. Hall (R-Tex.)), *available at* http://www.Energycommerce.house.gov/108/Hearings/06242003hearing968/print.htm. (last visited May 4, 2004).

[18] DAVIS & DIEGEL, *supra* note 6, at 6-12, tbl. 6.8. These two uses account for 75% of U.S. hydrogen consumption. *See also* AMERICAN CHEMICAL SOCIETY, CHEMISTRY IN THE ECONOMY 286 (1973).

[19] *The Hydrogen Energy Economy, Hearings Before the Subcomm. on Energy and Air Quality of the House Comm. on Energy and Commerce*, 108th Cong. 61 (2003) (statement of Gregory M. Vesey,

main source of power.[19] The current level of hydrogen production and use is about 9 million tons per year in the United States and 40 million tons per year worldwide.[20] There were 81 gaseous hydrogen plants in the United States in 2003, and 10 liquid hydrogen plants. Most of these plants produce hydrogen as part of another process, e.g., petroleum refining, ammonia production, and methanol production.[21]

Whether hydrogen use becomes significant depends on the success of the public and private entities involved in making the hydrogen economy a reality. Optimism prevails at DOE, but critics see the barriers to widespread commercial use of hydrogen as an energy carrier to be insurmountable during the next few decades. Technical, institutional, environmental, and market barriers exist for the production,[22] storage,[23] delivery,[24] fueling, and use of hydrogen.

A. Production

Hydrogen can be created from different fuel sources, some renewable, some nonrenewable. These sources are not all equally technologically advanced, and they create different types and quantities of pollution when hydrogen is generated.[25] It is unknown whether any single technology can produce the amount of hydrogen necessary to meet U.S. energy needs. DOE's National Hydrogen Energy Roadmap (Roadmap) predicts that when hydrogen is well established as an energy carrier, the U.S. hydrogen demand will be 40 million tons per year,[26] which is the present worldwide production level. To fully replace gasoline in light-duty vehicles in the United States would require 110 million tons of hydrogen per year.[27] The Roadmap projects that a demand for hydrogen fuel for approximately 25 million homes or 100 million automobiles (fuel cell-powered) would require 140 large coal or biomass gasification plants, or 100 nuclear plants whose power was dedicated to producing hydrogen, or 1 million small neighborhood electrolysis systems. A fleet of 100 million fuel cell-powered automobiles might require 67,000 vehicle refueling stations (which is one-third of the number of gasoline stations today) to meet consumer expectations.[28] The Roadmap's forecast implies that hydrogen will supply a fraction, though a sizeable one, of the total U.S. energy demand.

Hydrogen can be developed from coal[29] using one of several methods. Heavy oils, petroleum coke, biomass, and municipal waste also can be used to produce hydrogen. The primary method of obtaining hydrogen from coal is through coal gasification, which is costly.[30] It involves combining coal with oxygen and steam to produce "syngas," which contains primarily hydrogen and carbon monoxide (CO), and then putting the syngas through a process that converts it into CO_2 and hydrogen.[31] That mixture is then separated through pressure swing adsorption (PSA), a technology that adsorbs the hydrogen onto a porous material and releases it at lower pressures.[32] The hydrogen produced by coal gasification contains contaminants that must be removed before it can be used in a hydrogen fuel cell. To accomplish this result requires catalysts that resist poisoning by the contaminants.[33] Cost-effective technologies need to be developed to produce clean hydrogen.

The National Academy of Sciences stated in their Vision 21 Review that, by 2015, when the go/no go decision is supposed to be made on developing a hydrogen economy, coal technology will not be ready.[34] Nevertheless, the coal industry is working to perfect integrated gasification combined-cycle (IGCC) plants. In 2000, the National Coal Council reported that IGCC plants can compete with natural gas plants when gas costs $4 per million cubic feet (mcf); gas prices in 2003 generally exceeded $5 per mcf.[35] IGCC plants heat coal, water, and oxygen under high pressure to produce a gas of hydrogen and CO that can, with minor modifications, be used in gas-fired electric power plants. The IGCC plants also produce chemicals and diesel fuel as part of the conversion process. The relative amounts of syngas used to produce electricity or chemicals depend on market demand.[36]

President, ChevronTexaco Technology Ventures), *available at* http://energycommerce.house.gov/108/Hearings/06242003hearing968/print.htm (last visited May 4, 2004) [hereinafter *Hydrogen Economy Hearings*]. Ballard Power has developed "stand-alone back-up power generators" that use natural gas as a fuel and convert it to hydrogen-rich gas. Cook, *supra* note 9, at 11-12.

[20] *Hydrogen Economy Hearings*, *supra* note 19, at 57 (prepared statement of Francis R. Preli Jr., Vice President Engineering, UTC Fuel Cells). UTC has manufactured 225 stationary 200 kilowatt (kw) fuel cells for customers all over the world.

[21] Davis & Diegel, *supra* note 6, at 6-11, tbl. 6.7.

[22] U.S. DOE, Multi-Year Research Plan, Technical Plan—Hydrogen Production 3-2 to 3-17 (2003) [hereinafter Multi-Year Hydrogen Production].

[23] Office of Solid Waste and Emergency Response (OSWER), U.S. EPA, Emerging Issues in the Management of Waste Streams Related to Fuel Cells 14 (Strategic Monitoring and Trends Project, Analytical Paper No. 1, 2003) [hereinafter OSWER Report].

[24] U.S. DOE, Multi-Year Research Plan, Technical Plan—Hydrogen Delivery 3-33 (2002), *available at* www.eere.energy.gov/hydrogenandfuelcells/mypp/pdfs/3.2_delivery.pdf (last visited May 4, 2004) (problems include "lack of infrastructure," "cost and energy efficiency," "infrastructure trade offs," and barriers (*id.* at 3-35)) [hereinafter Multi-Year Hydrogen Delivery].

[25] *See* Multi-Year Program Benefits, *supra* note 8, at 2-9.

[26] U.S. DOE, National Hydrogen Energy Roadmap 11 (2002), *available at* http://www.eere.energy.gov/hydrogenandfuelcells/pdfs/national_h2_roadmap.pdf (last visited June 16, 2004) [hereinafter Hydrogen Energy Roadmap].

[27] National Research Council, The Hydrogen Economy: Opportunity, Costs, Barriers, and R&D Needs xvi (prepublication copy 2004) [hereinafter The Hydrogen Economy].

[28] *Id.* at 11, 14. Hydrogen refueling stations are not cost effective as yet. There were between 10-15 hydrogen refueling stations in the United States as of May 2003. *Hydrogen Economy Hearing*, *supra* note 19, at 30 (testimony of Hon. David K. Gorman, Ass't Secretary for Energy Efficiency and Renewable Energy, U.S. DOE).

[29] Multi-Year Program Benefits, *supra* note 8, at 2-10.

[30] *DOE Highlights Growing Hydrogen Program*, Clean Coal Today, Fall/Winter 2003, at 6.

[31] *Id.*

[32] *Id.*

[33] American Physical Society, The Hydrogen Initiative, Executive Summary 6 (2004), *available at* http://www.aps.org/public_affairs/loader.cfm?url=commonspot/security/getfile.ofm&pageID=49633 (last visited May 11, 2004) [hereinafter The Hydrogen Initiative].

[34] Review of DOE's Vision 21 Research and Development Program—Phase I (National Academy of Sciences 2003), *available at* http://www.nap.edu/openbook/0309087171/html/R1.html (last visited May 11, 2004) [hereinafter Vision 21 Review].

[35] DeWitt John & Lee Paddock, *Clean Air and the Politics of Coal*, Issues Sci. & Tech., Winter 2004, at 63, 68.

[36] U.S. DOE, Coproduction of Power, Fuels, and Chemicals 1 (2001) [hereinafter Topical Report No. 21].

IGCC plants provide lower cost, more efficient, and less polluting energy conversion than conventional hydrogen production from coal.[37] Industry, however, may be unwilling to invest in expensive technology, such as IGCC, which provides significant reductions in CO_2 emissions, unless there are governmental restrictions on CO_2 emissions.

The most common method used today to produce hydrogen is steam methane reforming (SMR) of natural gas,[38] which is used to make about one-half of the 49.5 million tons of hydrogen produced worldwide each year and more than 90% of the hydrogen produced in the United States.[39] Natural gas processing plants, known as reformers, use steam and catalytic processes to separate natural gas molecules into hydrogen and carbon-based compounds including CO_2.[40]

The process of producing hydrogen from fossil fuels requires more energy than is contained in the hydrogen. Why is a process with a net energy loss being pursued? The answer is that hydrogen fuel has a value greater than the coal, natural gas, or electric power used to produce it. With coal presently costing about $0.82 per million Btu and gasoline selling for over $15 per million Btu, this process could be viable.[41] But costs must be reduced if hydrogen is to compete with gasoline. Current hydrogen production technologies produce hydrogen at four times the cost of gasoline.[42] When used in a fuel cell, which is significantly more efficient than an internal combustion engine, the high cost of hydrogen is partially offset.[43] Some experts believe hydrogen can be competitive with gasoline selling at prices in the $2 per gallon range,[44] which is not occurring.

Hydrogen also can be produced through electrolysis, which decomposes water into hydrogen and oxygen using electricity. The process involves electrolyzers that are the opposite of fuel cells. Water and electricity are the inputs, and hydrogen and oxygen are the output. Electrolyzers operate at about a 70-80% efficiency. The market value of hydrogen is about eight times the cost of base load electricity from a coal-fired generating plant needed to produce it,[45] but high capital costs for electrolyzers limit their current use to niche markets where high costs for electricity are acceptable. These markets include manufacturers of semiconductors, specialty metals such as titanium, and glass manufacturers.[46] When electrolyzers are combined with fuel cells, they also are economical for users needing backup power, such as data processing centers or communications systems for whom electric power at four times the cost of primary power (on a kilowatt (kw) basis) is acceptable.[47]

The long-term value of the electrolysis process is its potential for dealing with the intermittent nature of electric power produced by solar or wind systems.[48] Electricity, when not needed by the grid, can be used to produce hydrogen which is then available to produce electricity on demand. If the value of the hydrogen as fuel is greater than the value of the electricity used in its production, it makes economic sense to produce it. The challenge is to find excess electric capacity at a competitive price, because replacing the gasoline used in the United States with hydrogen produced by electrolysis would require more electricity than is sold in the country today.[49]

Another way of producing hydrogen that is in the early stages of development is photobiological hydrogen production. This process uses genetically engineered microorganisms to make hydrogen.[50] Certain algae can split water into hydrogen and oxygen without needing the expensive catalysts currently used to produce hydrogen in fuel cells, but commercially viable processes are not yet available.[51] There is also some support for research concerning hydrogen production from water power, fusion,[52] and biomass.[53]

In addition, hydrogen can be produced using electricity generated by nuclear power.[54] Nuclear power does not generate conventional pollutants or greenhouse gas (GHG) emissions nor does it require imported fuel. However, public tolerance for nuclear power is low, and mistrust of nuclear power would likely preclude the construction of the many new nuclear power plants needed for a hydrogen economy based on this technology. But some members of the U.S. Congress support nuclear power.[55] The major problem with nuclear energy is its cost. New nuclear power may cost twice as much per delivered kw hour (kwh) as wind power, 5 to 10 times as much as co-producing electricity and heat using natural gas, and 3 to 30 times as much as reducing demand for electricity through end-use efficiency improvements.[56]

B. Delivery of Hydrogen

Hydrogen can be produced from large-scale industrial processes using natural gas at a cost less than gasoline per unit of energy. However, while relatively inexpensive to produce, hydrogen is inherently difficult and expensive to transport, store, and distribute.[57] Methods for delivery and storage of hydrogen from centralized production facilities include pipelines, tanker trucks, and trains. Pipelines can move either hydrogen, hydrogen mixed with natural gas, or other fuels that can be converted to hydrogen at the destination site. Hydrogen can be shipped as a high-density gas or as a liquid, and each method of shipping has advantages and

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[37] *Id.*; VISION 21 REVIEW, *supra* note 34.

[38] MULTI-YEAR PROGRAM BENEFITS, *supra* note 8, at 2-10.

[39] JOSEPH J. ROMM, THE HYPE ABOUT HYDROGEN 72 (2004) [hereinafter THE HYPE ABOUT HYDROGEN].

[40] Chip Schroeder, *Hydrogen From Electrolysis*, University of California-Davis Conference on Transportation and Energy 5 (Aug. 1, 2003) [hereinafter Schroeder].

[41] Schroeder, *supra* note 40, at 8.

[42] THE HYDROGEN INITIATIVE, *supra* note 33, at 1.

[43] Daniel Sperling & Joan Ogden, *The Hope for Hydrogen*, ISSUES SCI. & TECH., Spring 2004, at 82, 84.

[44] THE HYDROGEN INITIATIVE, supra note 33, at 1.

[45] *Id.* at 4.

[46] *Id.* at 5.

[47] *Id.* at 6.

[48] Schroeder, *supra* note 40, at 2.

[49] THE HYPE ABOUT HYDROGEN, *supra* note 39, at 76.

[50] MULTI-YEAR PROGRAM BENEFITS, *supra* note 8, at 3-5, 3-7, 3-8.

[51] THE HYDROGEN INITIATIVE, *supra* note 33, at 7.

[52] MULTI-YEAR PROGRAM BENEFITS, *supra* note 8, at 2-11.

[53] NATIONAL VISION, *supra* note 10, at 4.

[54] MULTI-YEAR PROGRAM BENEFITS, *supra* note 8, at 2-10, 2-11.

[55] *See Hydrogen Economy Hearings*, *supra* note 19, at 5 (prepared statement of Hon. C.L. "Butch" Otter (R-Idaho)).

[56] Craig Lambert, *The Hydrogen-Powered Future*, HARV. MAG., Jan./Feb., 2004, at 30, 34 [hereinafter Lambert].

[57] David W. Keith & Alexander E. Farrell, *Rethinking Hydrogen Cars*, 301 SCIENCE 315 (2003).

disadvantages. Delivery is especially important to the development of a hydrogen-based economy because it now is about five times more expensive to deliver hydrogen to dispersed small users than it is to produce hydrogen.[58] Technology advances that reduce delivery costs are needed. Hydrogen enjoys an inherent advantage of being the fuel that is the most concentrated energy carrier. A kilogram (kg) of hydrogen (2.2 pounds) carries about the same energy as a gallon of gasoline (6.2 pounds).[59] But because hydrogen is a light weight gas, its energy value on a volume basis is low.

1. Pipelines[60]

The use of natural gas pipelines to transport hydrogen was first suggested in the 1930s, by the German turbine designer Franz Lawaczeck.[61] Today there is some use of pipelines to transport hydrogen. A company called Air Products maintains a few hundred miles of hydrogen pipelines throughout the world, including in the United States.[62] That company's pipelines transport nearly 2,000 tons of hydrogen per day.[63]

In transporting hydrogen through pipelines, it can either be mixed with natural gas or the pipelines can be used for hydrogen alone. There are problems with each method: using pipes designed for natural gas to move hydrogen can cause what is known as embrittlement. To use pipelines for hydrogen transport requires either new materials resistant to embrittlement to be developed or some other way of successfully using the current pipes will have to be discovered. If pipelines are used to move both natural gas and hydrogen simultaneously, methods will have to be developed to separate the two fuels once they reach their destinations. Methanol, natural gas, or ethanol could be transported by pipeline to a site and converted to hydrogen onsite. Conversion of these fuels to hydrogen, however, is currently limited by the cost.[64]

The cost of building a new infrastructure to pipe hydrogen would be enormous, and the absence of such an infrastructure is one of the most significant barriers to hydrogen's viability as a widely used fuel.[65] The easiest way to transport hydrogen long distance (1,000 miles) is in liquid form,[66] but hydrogen is rarely used in that form and cooling it to a liquid and then returning it to a gas requires additional energy, making the process inefficient and costly.[67]

2. Road, Rail, and Waterway Options

Hydrogen potentially could be transported in compressed gas or cryogenic liquid trucks, tube trailers, barges, or rail cars.[68] However, the amount of hydrogen that could be transported would be smaller than the amount that pipelines could carry.[69] Hydrogen could not be carried as far because the size and weight of the hydrogen-containing metal cylinders limits its practical transportation to 100 miles,[70] though distances of 1,000 miles are possible with the use of superinsulated tankers, rail cars, and barges transporting liquid hydrogen.[71] If trucks are used to deliver hydrogen, the energy density of liquid hydrogen is low so it would require five times more trucks of hydrogen than of conventional fuel to supply a refueling site[72]; a 27-ton tanker truck can carry only enough hydrogen for about 60 fill-ups.[73] Thus, a great deal of additional diesel fuel would likely be consumed in delivering hydrogen. The high costs of hydrogen delivery may make on-site production a viable alternative; this is discussed below.

C. Storage of Hydrogen

Storage dilemmas may ultimately be the biggest obstacle to successful widespread hydrogen use,[74] especially for use in mobile sources.[75] Viable hydrogen storage requires a technology breakthrough, and it is hard to know when the needed scientific discovery will occur.[76] Hydrogen can be stored and delivered in several forms: low pressure or compressed gas,[77] cryogenic liquid,[78] recyclable liquid chemical carriers,[79] or stored in a solid in which hydrogen molecular are either absorbed into a solid or chemically bound up in the storage medium.[80] To liquify hydrogen requires it to be cooled below -423 degrees Fahrenheit (F) (-253 degrees Celsius (C)), which requires a significant energy input, and hydrogen is lost through evaporation.[81] Compressed gas storage is the most "mature" technology for hydrogen storage, and storage tank technology is advancing, allowing greater compression of hydrogen in storage tanks.[82] The compression process, however, requires significant energy.[83] To store hydrogen as a gas requires new materials that do not have embrittlement problems, do not leak, and that can safely store the fuel at high pressure.

Solids that can be used as carriers for hydrogen include

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[58] THE HYPE ABOUT HYDROGEN, *supra* note 39, at 85.

[59] Lambert, *supra* note 56, at 35.

[60] MULTI-YEAR HYDROGEN DELIVERY, *supra* note 24, at 3-32.

[61] THE KEYS TO THE CAR, *supra* note 14.

[62] *The Hydrogen Fuel Infrastructure*, *supra* note 15, at 68.

[63] *Id.*

[64] MULTI-YEAR HYDROGEN DELIVERY, *supra* note 24, at 3-31.

[65] *The Hydrogen Fuel Infrastructure*, *supra* note 15, at 66.

[66] *Id.* at 67-68.

[67] U.S. DOE, DRAFT, MULTI-YEAR RESEARCH, DEVELOPMENT, AND DEMONSTRATION PLAN, TECHNOLOGY PLAN—HYDROGEN STORAGE 3-44 (2003) [hereinafter MULTI-YEAR HYDROGEN STORAGE].

[68] MULTI-YEAR HYDROGEN DELIVERY, *supra* note 24, at 3-31.

[69] *The Hydrogen Fuel Infrastructure*, *supra* note 15, at 67.

[70] *Id.* The National Hydrogen Energy Roadmap cites the range as between 100 and 200 miles for high-pressure cylinders and tube trailers. HYDROGEN ENERGY ROADMAP, *supra* note 26, at 13.

[71] HYDROGEN ENERGY ROADMAP, *supra* note 26, at 13.

[72] *Well-to-Wheels Analysis of Future Automotive Fuels and Powerrains in the European Context* (European Comm'n Joint Research Center, Version 16, 2004), *available at* http://ies.jrc.cec.eu.int/Download/eh (last visited May 11, 2004).

[73] Lynn J. Cook, *Great Balls of Hydrogen*, FORBES, Jan. 20, 2003, at 92.

[74] *Id.* at 67.

[75] OSWER REPORT, *supra* note 23, at 14.

[76] *Hydrogen Economy Hearings*, *supra* note 19, at 20 (testimony of David K. Gorman, Ass't Secretary for Energy Efficiency and Renewable Energy, U.S. DOE).

[77] MULTI-YEAR HYDROGEN DELIVERY, *supra* note 24, at 3-31.

[78] *Id.*

[79] THE KEYS TO THE CAR, *supra* note 14.

[80] THE HYDROGEN INITIATIVE, *supra* note 33, at 7.

[81] Lawrence D. Burns et al., *Vehicle of Change*, SCI. AM., Oct. 2002, at 65. *The Hydrogen Fuel Infrastructure*, *supra* note 15, at 66; HYDROGEN ENERGY ROADMAP, *supra* note 26, at 17.

[82] HYDROGEN ENERGY ROADMAP, *supra* note 26.

[83] THE HYDROGEN INITIATIVE, *supra* note 33, at 7.

complex metal hydrides (among these, DOE is focusing on alanates),[84] chemical hydrides (pursued because of their safety and smaller volume, but they are expensive partly because the spent fuel must be recycled),[85] carbon nanotubes (the most promising carbon materials for hydrogen storage),[86] graphite nanofibers, or new metal-organic framework (MOF) materials.[87] To use solid chemicals requires new cost-effective technologies to be developed.[88]

Each storage method has its own strengths and weaknesses and, while compressed gas storage may be the most developed technology, none has emerged as a clear choice.[89] Storage of hydrogen as compressed gas, solid metal hydrides, and chemical hydrides is problematic "because hydrogen molecules will migrate into the matrix of the metal."[90] At this time, the technology is too inefficient to be a desirable method.[91]

In 2003, there were only 14 storage terminals in the United States for gaseous hydrogen storage and 3 storage terminals for liquid hydrogen.[92] When hydrogen is produced in centralized facilities, most commonly by steam methane reforming of natural gas, it must be delivered and stored at the refueling station as a liquid or gas. If delivered as a liquid, a vaporizer is used to convert the hydrogen to a gas and a compressor is used to increase its pressure. Research vehicles using hydrogen are designed to have fuel delivered at high pressure of typically 3,600 or 5,000 pounds per square inch (psi).[93] Because of the high cost and technical difficulties of delivering and storing hydrogen, a better approach is to produce the hydrogen near the point of end use.[94] But on-site production of hydrogen is more costly than producing it in industrial facilities where the economy of large scale operations lowers the cost of hydrogen production. Service stations dispensing hydrogen could use on-site electrolyzers to produce hydrogen with on-site compression and storage of gaseous hydrogen or use on-site natural gas reforming with on-site compression and storage.[95] The hydrogen produced on-site can be stored in storage tanks on-site or in the vehicles.[96]

DOE has given attention to storage of hydrogen onboard automobiles for use in fuel cells. Low temperature storage in a motor vehicle does not appear to be a useful option. A liquid oxygen system loses up to 1% a day by boiling and up to 30% during filling. Moreover, insulation must be sufficient to keep the hydrogen at a near absolute zero temperature.[97]

Compressed gas storage is the technology of choice but, at this time, it is inadequate. In order for hydrogen-fueled automobiles to have enough range to be useful to consumers (300 to 400 miles),[98] hydrogen would have to be stored at 350-700 bar, a pressure much higher than is used today in industry.[99] The hydrogen stored on-board a vehicle would have to be stored in such a way that it would fit in a small enough space not to take away interior or storage space, and it would have to be light.[100] DOE and others have suggested that hydrogen on-board storage technology first be tested on vehicle fleets (like delivery vehicles or buses) because they are used locally and are refueled centrally.[101] Three kg of hydrogen would be required for a 100-150 mile range.[102] For 300 to 400 mile driving ranges, the expectation of the average automobile owner, 5 kg of hydrogen would have to be stored on-board a small vehicle.[103] Current prototype vehicles use carbon-fiber tanks to store hydrogen at 5,000 psi, but this is inadequate to support long distance travel. Tanks are available that can operate at 10,000 psi, and some have been tested at 20,000 psi.[104] Such tanks could be used to increase the distance vehicles could travel on a tank of fuel.

Another approach is to use chemical hydrides, compounds that contain hydrogen, which can release hydrogen gradually and then be recharged. Hydrogen can be stored in vehicles as a chemical hydride for $8 per kwh, as a complex metal hydride for $16 per kwh, or as liquid hydrogen for $6 per kwh. DOE's goal is to get storage costs to $4 per kwh by 2010.[105] When stored using present technology, the energy content of the vehicle's hydrogen supply remains below what is needed to give the vehicle the range needed for consumer acceptance.[106] Moreover, metal-based compounds add too much additional weight for most motor vehicle use.[107]

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[84] *See* MULTI-YEAR HYDROGEN STORAGE, *supra* note 67, at 3-43. The National Hydrogen Energy Roadmap also cites alanates as better than other metal hydrides as to weight and temperature. HYDROGEN ENERGY ROADMAP, *supra* note 26, at 17.

[85] HYDROGEN ENERGY ROADMAP, *supra* note 26, at 18.

[86] *Id.* at 17. *See also* Online News Hour, *The Future of Fuel, Advances in Hydrogen Fuel Cell Technology* (Oct. 20, 2003), *available at* http://www.pbs.org/newshour/science/hydrogen/smalley.html (last visited June 16, 2004).

[87] *Hydrogen Economy Hearings*, *supra* note 19, at 73-74 (prepared statement of Johannes Schwank, Professor of Chemical Engineering, University of Michigan). Alanates, carbon storage structures, and chemical and metal hydrides are only in the developmental stage. HYDROGEN ENERGY ROADMAP, *supra* note 26, at 20.

[88] THE HYDROGEN INITIATIVE, *supra* note 33, at 5.

[89] HYDROGEN ENERGY ROADMAP, *supra* note 26, at 18, 33. Chemical hydrides may pose safety and health risks if, for example, traffic accidents caused exposure to humans. OSWER REPORT, *supra* note 23, at 15.

[90] *Hydrogen Economy Hearings*, *supra* note 19, at 20 (testimony of David K. Gorman, Ass't Secretary for Energy Efficiency and Renewable Energy, U.S. DOE).

[91] OSWER REPORT, *supra* note 23, at 14. The goal of the International Energy Association (IEA) is the development of storage systems that function at less than 80 degrees C and 1 atmospheric pressure, and have "at least 5 weight percent hydrogen recovery levels." Sodium alanate, in 2001, was believed to be closest to attaining these goals. *Id.* at 15.

[92] DAVIS & DIEGEL, *supra* note 6, at 6-11, tbl. 6-7.

[93] TIAX, LLC, CALIFORNIA CLEAN FUELS MARKET ASSESSMENT: 2003, at 4.6 (Prepared for the California Energy Commission, Aug. 2003) [hereinafter CALIFORNIA CLEAN FUELS].

[94] Schroeder, *supra* note 40.

[95] CALIFORNIA CLEAN FUELS, *supra* note 93, at 4.6.

[96] *Id.*

[97] Craig Davis et al., *Hydrogen Fuel Cell Vehicle Study 15*, AM. PHYSICAL SOC'Y, June 12, 2003 [hereinafter Davis et al.].

[98] HYDROGEN ENERGY ROADMAP, *supra* note 26, at 19.

[99] *The Hydrogen Fuel Infrastructure*, *supra* note 15, at 68. A bar is the metric measure for pressure; it is multiplied by 14.7 to get pressure in psi.

[100] HYDROGEN ENERGY ROADMAP, *supra* note 26, at 19.

[101] *Id.* at 22.

[102] *Id.*

[103] *Id.*

[104] Lambert, *supra* note 56, at 94.

[105] DAVIS & DIEGEL, *supra* note 6, at 6-13, tbl. 6.9.

[106] *Id.*

[107] Davis et al., *supra* note 97, at 15.

IV. Overview of Fuel Cell Technology

The most promising technology utilizing hydrogen is the fuel cell. Fuel cells can provide the benefit of electric vehicles while offering rapid acceleration and a range comparable to conventional motor vehicles.[108] The hydrogen fuel cell was first created in 1839 by Sir William Grove.[109] Grove's fuel cell was not very practical; it produced only about one volt of electricity, the platinum electrodes were prone to corrosion, and the materials used were not stable.[110] Francis Bacon developed a practical alkaline fuel cell in the 1950s, using electrodes of "porous sintered nickel powder."[111] Hydrogen fuel cells have been used in some capacity for over 35 years, and DOE has been promoting hydrogen power to Congress as a potentially viable energy option for over 25 years.[112]

Fuel cells can be used for both stationary source and mobile source applications. Fuel cells produce direct current electricity, which must be converted to alternating current if it is to be transported via the power grid.[113] Hydrogen fuel cells combine hydrogen and oxygen to produce water[114] and electricity.[115] The process is silent and usually is pollutant-free.[116] Using devices called reformers, gasoline, methanol, or natural gas can be converted to hydrogen and CO_2 and the hydrogen is used by the fuel cell to produce electrical energy.[117] Methanol reformers operate at the lowest temperature and pressure and, therefore, are the lowest cost reformers.[118] Using reformers minimizes the problems involved in the storage and transportation of hydrogen. However, building vehicles with reformers and fuel cells is difficult, and the technology to utilize this approach is not commercially available. Because using hydrogen fuel directly is easier than using a reformer to convert another fuel to hydrogen, most vehicle fuel cell research has been directed toward using hydrogen stored in the vehicle to run direct-hydrogen fuel cells. Direct-hydrogen vehicles have the potential to provide the best fuel economy of any known practicable propulsion technology.[119]

Hydrogen fuel cells are significantly more thermally efficient than internal combustion engines which have about 30% conversion efficiency.[120] Efficiency might be somewhat lessened over the life of a fuel cell if corruption from CO_2 or other substances occurs, and the technology to prevent corruption has not yet been developed. Fuel cells are currently 40-50% efficient at full power, 60% efficient at one-quarter power, and up to 80% efficient for combined heat and power applications.[121] However, there are technical limitations to efficient operation of fuel cells, and their use is not yet cost effective. None of the fuel cell types used for stationary source application exceed the efficiency of a modern gas-fired electric power plant.[122]

Fuel cells are classified according to the kind of electrolyte used at the core of the fuel cell in the cell's membrane.[123] They operate like "open batteries," producing electricity as long as they are supplied with fuel and oxygen (which may come from the air).[124] The five types of fuel cells are the following: (1) phosphoric acid fuel cells (PAFCs); (2) alkaline fuel cells (AFCs), which are the oldest technology; (3) solid oxide fuel cells (SOFCs); (4) proton exchange membrane (PEM) fuel cells; and (5) molten carbonate fuel cells (MCFCs).[125] All current fuel cell types have problems with cost, reliability, and durability.[126]

Some stationary PAFC units are in use as back-up generators, power grid support, and in buses,[127] however, they are expensive to produce and are not as promising a technology for passenger vehicles as PEM fuel cells.[128] PEM fuel cells have been used in fuel cell concept cars by major automobile manufacturers since the late 1980s.[129] One of the major obstacles to commercialization of these fuel cells is the cost of the platinum catalysts necessary to make the fuel cell work.[130] PEM-powered vehicles can convert hydrogen to electricity at 40-60% efficiency, which is about twice the efficiency of the standard internal combustion engine.[131] Ballard Power, a Canadian company, has made advances in PEM fuel cells by reducing the amount of platinum required for the catalysts and increasing the power density of the cells.[132] Los Alamos National Laboratory and Texas A&M University also have reduced the amount of platinum required in PEM fuel cells, and Los Alamos has been able to reduce catalyst poisoning from trace fuel impurities.[133] PEM fuel cells are easily compromised by CO, and therefore require high purity hydrogen. They must have an exter-

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[108] Sperling & Ogden, *supra* note 43, at 82, 84.

[109] Cook, *supra* note 9, at 2.

[110] *Id.* at 3.

[111] *Id.* at 4.

[112] Pamela Najor, *Requirement for "Zero-Sulfur" Diesel Fuel Needed in Final Energy Bill, Dingell Says*, 33 Env't Rep. (BNA) 1315 (June 14, 2002). DOE was created in 1977 by DOE's Organization Act, 42 U.S.C. §7101 (2000).

[113] ENERGY ALTERNATIVES: A COMPARATIVE ANALYSIS 12-32 (Science and Public Policy Program, University of Oklahoma, 1975).

[114] HYDROGEN ENERGY ROADMAP, *supra* note 26, at 23.

[115] Lambert, *supra* note 56, at 34.

[116] Cook, *supra* note 9, at 1.

[117] Russell Moy, *Tort Law Considerations for the Hydrogen Economy*, 24 ENERGY L.J. 349, 350 (2003) [hereinafter Moy].

[118] CALIFORNIA CLEAN FUELS, *supra* note 93, at 3.2.1.

[119] *Id.* at 3.2.2.

[120] MULTI-YEAR PROGRAM BENEFITS, *supra* note 8, at 2-7, 2-12; CALIFORNIA CLEAN FUELS, *supra* note 94, at 3.2.2.

[121] HYDROGEN ENERGY ROADMAP, *supra* note 26, at 23.

[122] *Id.* at 26.

[123] *Hydrogen Economy Hearings*, *supra* note 19, at 74; OSWER REPORT, *supra* note 23, at 4.

[124] OSWER REPORT, *supra* note 23, at 4.

[125] HYDROGEN ENERGY ROADMAP, *supra* note 26, at 24.

[126] *Id.* at 24.

[127] *Id.* at 23.

[128] THE HYPE ABOUT HYDROGEN, *supra* note 39, at 27.

[129] HYDROGEN ENERGY ROADMAP, *supra* note 26, at 23; THE HYDROGEN ECONOMY, *supra* note 27, at xviii.

[130] HYDROGEN ENERGY ROADMAP, *supra* note 26, at 25.

[131] Don Anair, *Hydrogen Fuel Cells*, CATALYST, Spring 2004, at 1. The PEM fuel cell uses hydrogen stored in the vehicle and oxygen in the air to generate electricity. Hydrogen enters the fuel cell and a catalyst, usually platinum, splits the hydrogen into positively charged hydrogen ions and negatively charged electrons. The positive ions pass through the electrolyte, a PEM. The electrons are forced to travel around the PEM, which creates electricity. A PEM fuel cell produces very little electricity. To produce the power needed by a vehicle requires hundreds of fuel cells to be combined in a fuel cell stack. The fuel cell stack, an air compressor to deliver oxygen, a cooling system, and a hydrogen storage system make up the fuel cell vehicle's propulsion system. *Id.*

[132] Cook, *supra* note 9, at 8.

[133] *Id.*

nal reformer if they are to be fueled by natural gas.[134] PEM fuel cells work at low temperatures, about 150 degrees F, which make them ideal for motor vehicles because they can reach full power seconds after start-up; other types of fuel cells operate at high temperatures and take more time to warm up than motorists would tolerate, which is why they are best used in stationary fuel cells.[135]

AFCs produce power and potable water. The National Aeronautics and Space Administration (NASA) has used pure hydrogen and pure oxygen in AFCs onboard the space shuttle for the past 30 years.[136] In flight, astronauts drink pure water that is the byproduct of the fuel cell reactions.[137] Fuel cells are more reliable in space because they are not subject to corruption from atmospheric components, particularly CO_2, that shorten fuel cell life.[138] AFCs are not as successful on earth because CO_2 in the atmosphere "poisons" the electrolyte by reacting with the hydroxide ions from the electrolyte to form a carbonate, which reduces the concentration of hydroxide ions in the electrolyte.[139]

MCFCs and SOFCs are used for stationary electric power combined-cycle and cogeneration and in large trucks.[140] MCFCs operate at high temperatures (1,200 degrees F or higher). This allows them to produce hydrogen directly from natural gas, ethanol, or methanol.[141] These direct fuel cells do not require an external reformer to generate hydrogen which lowers overall costs and increases efficiency above that of PEM fuel cells.[142] Their high temperature operation allows nickel rather than costly platinum to be used as the catalyst and the MCFC is able to resist CO poisoning better than PEM fuel cells. Their high temperature operation allows for cogenerating heat.[143] They are not suitable for transportation applications because they are slow to reach operating temperatures and a 250 kw unit is the size of a railroad car and weighs 40 tons.[144] SOFCs also operate at high temperatures using ceramic as the electrolyte. Their advantage is they have higher electric efficiencies than PEM fuel cells, they do not need an external reformer, and they produce useable heat.[145] SOFCs have been used as stationary electric power sources, but they continue to have technical and cost problems that limit commercialization.[146]

Some researchers advocate burning hydrogen in internal combustion engines as a transitional step toward full use of hydrogen in fuel cells.[147] Hydrogen used in internal combustion engines does not have to be purified to the extent required for fuel cell use, hence, it is less costly to produce.[148] DOE expects this combustion technology to play a role in the hydrogen economy,[149] because it may be a lower cost technology that could be implemented sooner than fuel cells and could help facilitate development of a hydrogen delivery infrastructure.[150]

California's Low Emission Vehicle Program may give a boost to hydrogen fuel cell cars. It requires, beginning in 2003, that 10% of passenger cars delivered for sale in California from medium or large sized manufacturers to be zero emission vehicles (ZEVs).[151] Regulatory changes in 2003, allow manufacturers the option to produce fuel cell vehicles to meet ZEV requirements.[152] The initial target is to have each manufacturer deploy up to 250 fuel cell vehicles by 2008.[153] In 2004, the California Air Resources Board (CARB) announced that Ford Motor Company, General Motors Corporation (GM), Toyota Motor Corporation, and Daimler-Chrysler Company each should have a demonstration fuel cell electric vehicle by the end of the year.[154] California also created the Fuel Cell Technical Advisory Panel to assess fuel cell technology and the California Fuel Cell Partnership, composed of CARB, the California Energy Commission, automobile makers, fuel cell developers, fuel companies, and government agencies.[155] The California Fuel Cell Partnership has several purposes, including demonstration of fuel cell electric vehicles, hydrogen infrastructure, fuel cell vehicle commercialization and public awareness.[156]

A few automobile models have been produced that use a hydrogen fuel cell, but they generally are not commercially available. The only hydrogen-powered fuel cell car government-certified for use on public roads is the Honda FCX. Automotive companies with fuel cell vehicle programs include Daimler-Chrysler, Ford, GM, Honda, PSA Peugeot-Citroen, Renault, Nissan Motor Co., Ltd. and Toyota.[157] Toyota built a fuel cell vehicle that was leased to Japan's Ministry of the Environment, but it had to be recalled for

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[134] THE HYPE ABOUT HYDROGEN, *supra* note 39, at 31.

[135] *Id.* at 12.

[136] *Fuel Cell History*, *at* www.fuelcellstore.com/information/fuel_cell_history.html (last visited Dec. 31, 2003).

[137] Cook, *supra* note 9, at 5.

[138] *Id.* at 6.

[139] *Id.* at 6.

[140] HYDROGEN ENERGY ROADMAP, *supra* note 26, at 24.

[141] THE HYPE ABOUT HYDROGEN, *supra* note 39, at 27.

[142] *Id.*

[143] *Id.* at 28.

[144] *Id.*

[145] *Id.* at 53.

[146] *Id.* at 30.

[147] *Hydrogen Economy Hearings*, *supra* note 19, at 74 (prepared statement of Johannes Schwank, Professor of Chemical Engineering, University of Michigan).

[148] Davis et al., *supra* note 97, at 11.

[149] HYDROGEN ENERGY ROADMAP, *supra* note 26, at 24.

[150] *Id.* at 29.

[151] Cook, *supra* note 9, at 8.

[152] CALIFORNIA CLEAN FUELS, *supra* note 93, at 3.2.

[153] *Id.* at 3.2. In 1990, CARB required 10% of all new vehicles offered for sale in California in 2003 to be electric-battery propelled. In 1996, the ZEV interim mandate for 1998-2002 vehicles was modified to require only a limited number of demonstration vehicles. In April 2003, with ZEV requirements on hold for 2003-2004 because of lawsuits brought by automakers, CARB adopted changes to be fully effective in 2005. Manufacturers have two options for meeting ZEV requirements. The first option is to meet the 2001 ZEV rule. This requires a manufacturer to produce a vehicle mix with 2% ZEVs, 2% advanced technology partial ZEVs (including hybrid electric and CNG vehicles), and 6% partial ZEVs that are low emission gasoline vehicles. The second option is a ZEV compliance strategy that allows manufacturers to produce fuel cell vehicles in numbers that are sales weighted up to 250 in 2008, and increasing to as many as 50,000 fuel cell vehicles in 2017. Battery electric vehicles may be substituted for up to one-half the fuel cell requirements, under both options a smaller number of partial or advanced technology partial ZEVs may be substituted. *Id.* at 3.1.3.

[154] CARB, *Consumer Information: Fuel Cell Electric Vehicles Fact Sheet* (Mar. 24, 2004), *at* http://www.arb.ca.gov/msprog/zevprog/factsheets/fuelcells_fs.pdf (last visited May 11, 2004).

[155] *Id.*

[156] *Id.*

[157] Burns et al., *supra* note 81.

safety reasons when hydrogen leaked and was not detected by the vehicle's sensors.[158]

Daimler-Chrysler's fuel cell car prototype is called the NECAR 5.[159] It runs on liquid methanol, which a fuel processor converts into CO_2 and hydrogen before using the hydrogen in its fuel cell.[160] It is twice as thermally efficient as an internal combustion engine and therefore emits less CO_2 than a similar fossil-fueled vehicle.[161] A hydrogen fuel cell van, a Mercedes Sprinter, from Daimler-Chrysler was delivered to the United Parcel Service (UPS) on October 9, 2003.[162] It has a 55 kw electric engine, a 150-kilometer (km) range, and a top speed of 120 km per hour.[163] GM has spent more than $1 billion on its fuel cell program and successfully reduced the size, weight, cost, and complexity of the fuel cell stack.[164]

Several states are performing hydrogen research, especially California, Illinois, and New York. California is the most involved state in research on hydrogen technologies; it has several projects underway.[165] In the private sector, many companies, including coal, oil, and automobile companies, have been involved in hydrogen research.[166] A few companies are entirely devoted to hydrogen technology.[167] A number of universities and research facilities are heavily involved in researching and developing new hydrogen technologies. For example, the University of Michigan is involved in fuel cell-powered automobiles,[168] the National Fuel Cell Center at the University of California developed a fuel cell automobile,[169] and Texas A&M is involved in fuel cell research.[170] Some nonprofit organizations are involved in consultations with DOE, and are listed as contributors in several government reports and studies on hydrogen.[171] Various foreign governments, including Japan, the European Union, Singapore, Korea, China and Canada, have been involved in hydrogen technology research.[172]

The first fuel cell vehicles to be used commercially are likely to be buses.[173] Georgetown University, in Washington, D.C., obtained three hybrid electric buses, one in 1994 and two in 1995.[174] These three buses, the Generation I fuel cell transit buses, used 50 kw PAFCs, fueled with methanol, which is converted into hydrogen that is used in the fuel cell.[175] Methanol was selected because it was easy to obtain and use.[176] The Generation II fuel cell transit buses were introduced in 1998 and 2000, and used a PAFC and PEM fuel cell, respectively, each 100 kw.[177] These two buses use methanol to produce the hydrogen on-board, and they capture energy using regenerative braking to give the buses surge power from traction batteries.[178] A traction battery is a battery that supplements the fuel cell power; traction batteries store energy they recover in a process called regenerative braking, and they provide surge power,[179] the extra power needed to accelerate and climb hills.[180] Both Generation II buses seat 40 passengers, have a 350-mile range, low emissions, and the power system weighs less than 2 tons.[181] The Phase III bus is still in the development stage; it will run on hydrogen only and will not be a hybrid.[182]

DOE is supporting a bus program at the University of Las Vegas that stores compressed hydrogen and burns it in an internal combustion engine (ICE). SunLine Transit Agency, in California's Coachella Valley, began using a hybrid hydrogen fuel cell bus in November 2002, and plans to acquire additional fuel cell buses in 2004. The California Fuel Cell Partnership plans to begin operating seven transit buses powered by direct-hydrogen fuel cells in 2004.[183]

If fuel cell vehicles are to become an important part of the transport system, there needs to be a major advance in cell

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[158] Moy, *supra* note 117, at 353.

[159] Cook, *supra* note 9, at 9.

[160] *Id.*

[161] *Id.*

[162] Daimler-Chrysler, *Daimler-Chrysler Hands Over Fuel Cell Sprinter Vehicle to UPS Parcel Service Today*, FUEL CELL TODAY, Oct. 9, 2003, *available at* http://www.fuelcelltoday.com/FuelCellToday/IndustryInformation/IndustryInformationExternal/NewsDisplayArticle/0%2C1602%2C3493%2C00.html (last visited Apr. 9, 2004).

[163] UPS, 2003 Press Releases, Fuel Cell Sprinter to be field-tested in Germany by UPS (Oct. 9, 2003), *available at* http://www.pressroom.ups.com/pressreleases/archives/archive/0,1363,4344,00.html (last visited Apr. 9, 2004).

[164] *Hydrogen Economy Hearings*, *supra* note 19, at 40 (statement of J. Byron McCormick, Executive Director, Fuel Cell Activities, GM Research and Development).

[165] *See* California Fuel Cell Partnership website on the Internet at http://www.drivingthefuture.org (last visited Apr. 18, 2004).

[166] *See Hydrogen Economy Hearings*, *supra* note 19, at 7 (prepared statement of Hon. John D. Dingell (D-Mich.)). Rep. Dingell mentioned research by GM and Chrysler. *See also Hydrogen Economy Hearings*, *supra* note 19, at 62 (prepared statement of Gregory M. Vesey, President, Technology Ventures, Chevron Texaco, and at 85, prepared ptatement of the American Petroleum Institute).

[167] *See Hydrogen Economy Hearings*, *supra* note 19, at 57 (prepared statement of Francis R. Preli Jr., Vice President Engineering, UTC Fuel Cells, and at 52, prepared statement of Catherine Rips, SunLine Transit Agency (monitoring several companies that work entirely or primarily with hydrogen)).

[168] *See Hydrogen Economy Hearings*, *supra* note 19, at 72 (prepared statement of Johnnes Schoank, Professor of Chemical Engineering, University of Michigan); *see id.* at 66.

[169] *Hydrogen Economy Hearings*, *supra* note 19, at 65 (prepared statement of Scott Samuelson, Director, National Fuel Cell Center, University of California).

[170] SECA Project Information, *2003 DOE Project Selections*, *at* http://www.fe.doe.gov/programs/powersystems/fuelcells/fuelcells_seca_2003sel_bkg_files/fuelcell_seca03sel_bkg.html (last visited Apr. 18, 2004). Other universities involved in hydrogen research include the University of Akron (*Hydrogen Economy Hearings*, *supra* note 19, at 6 (prepared statement of Hon. Sherrod Brown, D-Ohio), and Georgetown University).

[171] HYDROGEN ENERGY ROADMAP, *supra* note 26, at 44.

[172] *Hydrogen Economy Hearings*, *supra* note 19, at 48 (statement of Catherine Rips, Sunline Transit Agency).

[173] CALIFORNIA CLEAN FUELS, *supra* note 93, at 1.2.6.

[174] *Georgetown University Advanced Vehicle Development: The Fuel Cell Bus Program*, *at* http://fuelcellbus.georgetown.edu/files/guavdbrochure.pdf (last visited Apr. 9, 2004) [hereinafter *Georgetown Fuel Cell Bus Program*].

[175] *Id.*

[176] *Id.*

[177] *Georgetown University Advanced Vehicle Development: Program Details*, *at* http://fuelcellbus.georgetown.edu/text/overview2.html (last visited Apr. 8, 2004) [hereinafter *Georgetown Program Details*].

[178] *Georgetown Fuel Cell Bus Program*, *supra* note 174.

[179] *Ballard Power, Fuel Cell Technology: Transit Buses*, *at* http://www.ballard.com/td.asp?pgid=26&dbid=0 (last visited May 6, 2004).

[180] *Georgetown University, TBB General Information*, *at* http://fuelcellbus.georgetown.edu/tbbtech.cfm (last visited May 6, 2004).

[181] *Id.*; *Georgetown Program Details*, *supra* note 177.

[182] *Georgetown Program Details*, *supra* note 177.

[183] CALIFORNIA CLEAN FUELS, *supra* note 93, at 3.2.2., auto manufacturers, fuel providers, and fuel cell developers that work to demonstrate fuel cell vehicles.

membrane technology. Membranes must have high permeability and selectivity in gas separation. They must be highly conductive and durable in a high temperature corrosive environment. Numerous materials have been tested for potential replacement of the costly platinum currently used in fuel cells, but there has been no major breakthrough in membrane technology.[184] Fuel cells currently cost 10 times more than an internal combustion engine of equivalent power.[185] Others claim fuel cells cost about twice the cost of equivalent power from an internal combustion engine, even after taking into account the higher efficiency of fuel cells. Thus, the cost of fuel cells need to be cut dramatically to be competitive.[186]

V. The Bush Administration's Hydrogen Fuel Program

In 2002, the FreedomCAR program was launched to develop high-efficiency vehicles by focusing on fuel cells and hydrogen produced from renewable energy sources.[187] FreedomCAR is an industry-government cooperative effort, sponsored by DOE's Office of Energy Efficiency and Renewable Energy (EERE), to develop fuel cell vehicles. The FreedomCAR initiative aims to coordinate energy companies, automakers, utilities, state and local governments, and other appropriate interests in an effort to develop hydrogen vehicles and their infrastructure concurrently. This initiative has technology-specific goals for electric propulsion systems, fuel cells, and reformers.[188] If successful, the program could result in commercially viable fuel cell cars being available by 2015.[189] The infrastructure needed for fuel cell cars to operate is to be in place in 2020.[190] The FreedomCAR program includes plans to develop technology useful in hybrid vehicles, and to improve fuel economy in hybrid and gasoline-fueled vehicles, which will be useful when fuel cell vehicles are developed.[191] The FreedomCAR project involves cooperation between EERE and USCAR (which includes DaimlerChrysler, Ford, and GM).[192]

On January 28, 2003, in his State of the Union Address, President Bush announced a federal Hydrogen Fuel Initiative to be funded with an additional $720 million over 5 years from levels authorized for fiscal year (FY) 2003.[193] This initiative is aimed at reducing U.S. dependence on foreign petroleum by pursuing hydrogen fuel and fuel cell infrastructure development.[194] In a separate but related effort, on February 27, 2003, President Bush announced a $1 billion project, called FutureGen, to seek to develop a coal-based hydrogen and electric plant in 10 years.[195] DOE's Office of Fossil Energy is responsible for this power plant project that seeks, through gasification of coal, to produce hydrogen that is competitive in price with gasoline while producing electricity only 10% more expensive than current coal-generated electricity. This process would create significant amounts of CO_2, and one of the goals for FutureGen is to develop carbon sequestration technology to store the CO_2 deep in bedrock.[196] The program is to involve a consortium of the coal-fired electric power industry and the coal production industry that is to include the owners of at least one-third of U.S. coal and the producers of one-fifth of U.S. coal-fired electricity.[197] It is to include eastern and western coal producing entities and all types of coal.[198]

DOE is the lead agency in the Hydrogen Fuel Initiative, with other agencies involved including the U.S. Environmental Protection Agency (EPA), the U.S. Department of Defense (DOD), the U.S. Department of Transportation (DOT), the U.S. Department of Commerce (DOC), the National Institute of Standards and Technology (NIST), NASA, and the Office of Science and Technology Policy at the White House.[199] DOE's role is expected to increase due to its mandate from the White House, as expressed in the 2003 State of the Union Address.[200]

DOE has several offices working on hydrogen-related technology and the Hydrogen Fuel Initiative, including the EERE, the Office of Nuclear Energy, Science and Technology, the Office of Fossil Energy, and the Office of Science.[201] EERE controls most of the hydrogen and vehicle technology programs[202] and is the unofficial leader of DOE's efforts to develop useable hydrogen technologies.[203] It works with DOT to overcome institutional barriers to a hydrogen economy by forming technology partnerships with the private sector, creating codes and standards, and encouraging international cooperation.[204] EERE's hydrogen activities are primarily the responsibility of its Office of Hydrogen, Fuel Cells and Infrastructure Technologies Pro-

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[184] The Hydrogen Initiative, *supra* note 33, at 9.

[185] Davis et al., *supra* note 97, at 3; The Hydrogen Economy, *supra* note 27, at xviii.

[186] Schroeder, *supra* note 94, at 6.

[187] David & Diegel, *supra* note 6, at 6-9.

[188] Davis et al., *supra* note 97, app. B.

[189] U.S. DOE, Draft, Multi-Year Research, Development, and Demonstration Plan, Introduction 1-6 (2003) [hereinafter Multi-Year Research Introduction]; Davis & Diegel, *supra* note 6, at 6-9.

[190] *Hydrogen Economy Hearings*, *supra* note 19, at 5 (prepared statement of Hon. W.J. "Billy" Tanuin (R-La.), Chairman, Committee on Energy and Commerce).

[191] Multi-Year Program Benefits, *supra* note 8, at 1-2.

[192] *Id.* at 1-1, 1-2.

[193] Robert L. Bamberger, *Energy Policy: The Continuing Debate and Omnibus Energy Legislation* 11 (Congressional Research Service (CRS) Issue Brief for Congress, updated Feb. 23, 2004).

[194] Fact Sheet: Hydrogen Fuel: A Clean and Secure Energy Future (2003), *available at* www.whitehouse.gov/ news/releases/ 2003/02/20030206-2.html (last visited Oct. 7, 2003).

[195] Statement by the president, Feb. 27, 2003, *at* http://www.whitehouse.gov/news/releases/2003/02/20030227-11.html (last visited May 26, 3004).

[196] *Future Options for Generation of Electricity From Coal, Hearings Before the Subcomm. on Energy and Air Quality of the House Comm. on Energy and Commerce*, 108th Cong. 16 (2003). Statement of George Rudins, Deputy Ass't Secretary for Coal and Power Systems, Office of Fossil Energy, U.S. DOE, *available at* http://energycommerce.house.gov/108/Hearings/06242003hearing968/print.htm (last visited May 26, 2004).

[197] *Id.*

[198] *Id.*

[199] *Hydrogen Economy Hearings*, *supra* note 19, at 17 (testimony of David K. Gorman, Ass't Secretary for Energy Efficiency and Renewable Energy, U.S. DOE).

[200] *Id.*

[201] *Id.*

[202] *Id.*

[203] *Id.*

[204] *Hydrogen Economy Hearings, supra* note 19, at 17.

gram,[205] which is the lead organization for hydrogen production, delivery, and storage and fuel cells issues.[206] The goal of DOE's EERE is to develop a "full hydrogen economy by 2040."[207] There are nine focus areas in developing the hydrogen economy[208]: hydrogen production,[209] delivery,[210] and storage,[211] fuel cells,[212] safety,[213] education,[214] codes and standards,[215] technology validation,[216] and systems integration/analyses.[217]

Based on the Hydrogen Fuel Initiative, the government's role will be funding and encouraging faster hydrogen and fuel cell technology development—marketing and manufacturing are to be left to private companies.[218] DOE's hydrogen program is to have four phases. Phase I should last until 2015.[219] In 2015, based on achievement or non-achievement of specified milestones, DOE plans to decide whether to pursue full commercialization of hydrogen technology.[220] Phase II, from 2010 to as early as 2020, is Transition to the Marketplace, with mass marketing beginning in 2020 if a positive commercialization decision is made in 2015.[221] Phase III, beginning with the commercialization decision, is Expansion of Markets and Infrastructure, and Phase IV, Realization of the Hydrogen Vision, is the transition to the full hydrogen economy and is currently placed as 2025-2040.[222] According to Assistant Secretary David Garman, the hydrogen initiative receives almost daily attention from the DOE Secretary and frequent attention from the Council on Environmental Quality.[223] Most of the major technology-based targets of the Hydrogen Fuel Initiative are aimed at achievement by 2010.[224]

DOE's budget requests in recent years have had a significant allotment for hydrogen technology research and development (R&D).[225] In 2002, the total budget allotment for hydrogen and fuel cells was $75.6 million; in 2003, it increased to $95.5 million.[226] In FY 2004, the Energy and Water appropriations bill[227] provided $78 million for the development of hydrogen technology, but $37 million is specified expenditures that will not have much affect on advancing the hydrogen initiative.[228]

The Administration supports new energy legislation that includes a hydrogen and fuel cell program, but no new energy legislation has been enacted. The effort to pass comprehensive energy legislation however, is ongoing. The U.S. House of Representatives' approved its version of H.R. 6, the Energy Policy Act of 2003, on April 11, 2003. It contained authorization for the FreedomCAR project and for the Hydrogen Fuel Initiative.[229] H.R. 6 also included new authorizations for hydrogen R&D and infrastructure. The U.S. Senate version of the legislation was approved by the Senate on July 31, 2003.[230] The House version of H.R. 6 provided for the additional $720 million for hydrogen fuel, fuel cell and vehicle technology research. The Senate version of H.R. 6 required 100,000 hydrogen-fueled cars to be produced by 2010 and 2.5 million vehicles to be produced each year after 2020.[231] In November 2003, the conference committee reported H.R. 6, and the House approved the conference report on November 18, 2003. However, the legislation did not pass in the Senate.[232]

On February 12, 2004, Sen. Pete V. Domenici (R-N.M.) introduced S. 2095, which is a revised version of the prior year's H.R. 6. S. 2095 is estimated to cost $14 billion in contrast to H.R. 6's projected $31 billion cost.[233] The bill authorizes $2.1 billion for hydrogen fuel and fuel cell R&D over FY 2004 to FY 2008.[234] As of May 2004, the bill had not passed and there is not much expectation that it can be passed.[235]

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[205] MULTI-YEAR RESEARCH INTRODUCTION, *supra* note 189, at 1-6.

[206] THE HYDROGEN ECONOMY, *supra* note 27, at xxiii.

[207] MULTI-YEAR RESEARCH INTRODUCTION, *supra* note 189, at 1-9.

[208] *Id.*

[209] *See* MULTI-YEAR HYDROGEN PRODUCTION, *supra* note 22.

[210] MULTI-YEAR HYDROGEN DELIVERY, *supra* note 24.

[211] *See* MULTI-YEAR HYDROGEN STORAGE, *supra* note 67.

[212] U.S. DOE, DRAFT, MULTI-YEAR RESEARCH, DEVELOPMENT, AND DEMONSTRATION PLAN, TECHNICAL PLAN–FUEL CELLS (2003), *available at* www.eere.energy.gov/hydrogenandfuelcells/mypp/pdfs/3.4_fuelcells.pdf (last visited Mar. 16, 2004).

[213] U.S. DOE, DRAFT, MULTI-YEAR RESEARCH, DEVELOPMENT, AND DEMONSTRATION PLAN, TECHNICAL PLAN–HYDROGEN SAFETY (2003), *available at* www.eere.energy.gov/hydrogenandfuelcells/mypp/pdfs/3.7_safety.pdf (last visited Mar. 16, 2004).

[214] U.S. DOE, DRAFT, MULTI-YEAR RESEARCH, DEVELOPMENT, AND DEMONSTRATION PLAN, TECHNICAL PLAN–EDUCATION (2003), *available at* www.eere.energy.gov/hydrogenandfuelcells/mypp/pdfs/3.8_education.pdf (last visited Mar. 16, 2004).

[215] U.S. DOE, DRAFT, MULTI-YEAR RESEARCH, DEVELOPMENT, AND DEMONSTRATION PLAN, TECHNICAL PLAN–HYDROGEN CODES AND STANDARDS (2003), *available at* www.eere.energy.gov/hydrogenandfuelcells/mypp/pdfs/3.6_codes.pdf (last visited Mar. 16, 2004).

[216] U.S. DOE, DRAFT, MULTI-YEAR RESEARCH, DEVELOPMENT, AND DEMONSTRATION PLAN, TECHNICAL PLAN–TECHNOLOGY VALIDATION (2003), *available at* www.eere.energy.gov/hydrogenandfuelcells/mypp/pdfs/3.5_validation.pdf (last visited Mar. 16, 2004).

[217] MULTI-YEAR RESEARCH INTRODUCTION, *supra* note 189, at 1-7.

[218] *Hydrogen Economy Hearings, supra* note 19, at 11.

[219] *Id.* at 13.

[220] U.S. DOE, FUEL CELL REPORT TO CONGRESS (2003) (ESECS EE-1973) [hereinafter FUEL CELL REPORT].

[221] *Hydrogen Economy Hearings, supra* note 19, at 13.

[222] *Id.* at 14.

[223] *Id.* at 18.

[224] *Id.* at 19. On April 26, 2004, President Bush announced $350 million in funding of new hydrogen research. *See* Pamela Najor, *Bush Links Hydrogen Fuel Cell Progress to Environmental Protection Innovation*, 35 Env't Rep. (BNA) 954 (Apr. 30, 2004).

[225] U.S. DOE, DRAFT, MULTI-YEAR RESEARCH, DEVELOPMENT, AND DEMONSTRATION PLAN, APPENDIX A—BUDGETARY INFORMATION (2003), *available at* http://www.eere.energy.gov/hydrogenandfuelcells/mypp/pdfs/appendix.pdf (last visited May 11, 2004).

[226] *Id.* at A1.

[227] Pub. L. No. 108-137 (2003).

[228] THE HYDROGEN ECONOMY, *supra* note 27, at xxiii.

[229] *Hydrogen Economy Hearings*, *supra* note 19, at 5.

[230] The two bills are covered in *Omnibus Energy Legislation: Comparison of Major Provisions in House- and Senate-Passed Versions of H.R. 6, Plus S. 14* (CRS Report RL 32078 (2003)).

[231] *Energy Policy: The Continuing Debate, supra* note 193, at 12.

[232] *Id.*

[233] The differences between the two bills are summarized *at* http://energy.senate.gov/news/rep_release.cfm?id=217948 (last visited June 16, 2004).

[234] *Energy Policy: The Continuing Debate*, *supra* note 193, at 2.

[235] Martin Kady II, *The Energy Bill, Foiled Again*, CONGRESSIONAL QUARTERLY WKLY., May 4, 2004.

VI. Issues of Concern

There are serious problems in several areas that must be overcome if hydrogen is to be a viable fuel choice. Some areas of concern about hydrogen include safety, cost, technology development, consumer interest, competing fuels and techniques, its ability to reduce dependence on foreign oil, and environmental impacts.

A. Safety

When the hydrogen-filled dirigible, the *Hindenburg*, burned in New Jersey in 1937, the publicity helped make the public leery of using hydrogen.[236] Hydrogen is listed as a hazardous material by the DOT.[237] It requires little heat to combust and burns with an invisible flame.[238] Hydrogen has a low density[239] and, if stored under high pressure, there is a risk of explosion if the gas escapes, especially in an enclosed space. If stored as a liquid, it poses a danger of frostbite to handlers.[240] It has a wide "flammability range," able to burn when it constitutes between 4% to 74% of air by volume.[241] There are safety concerns, including the potential for an explosion. Hydrogen transport and storage systems need to be designed with the expectation that they could be a terrorist target; this will add to the expense.[242] If stored as a liquid in a motor vehicle, hydrogen may start to "vent" if the car is not used for several days; which is a fire hazard.[243] However, hydrogen diffuses quickly which reduces its safety risk, and it is not poisonous.[244]

Much of the focus on making hydrogen safer for use has been focused on leak detection and prevention. Tighter seals and various methods of leak detectors have been tested. However, NASA, the agency with the most experience dealing with hydrogen, advises its employees working in proximity to hydrogen to wave straw brooms in front of themselves as they walk—because the sacrificial broom's ignition is the only way of knowing whether hydrogen is burning.[245]

Adding a chemical with a strong odor to odorless hydrogen gas has been recognized as imperative, but it is unlikely a suitable substance can be found because hydrogen, the lightest gas, disperses faster than any chemical mixed with it, making an additive useless as a leak detector.[246] Even if this problem was solved, it would be difficult to find a chemical that would not corrupt fuel cells' catalysts.[247]

Serious liability risks attend any widespread use of hydrogen. Though conventional fuels are explosive, hydrogen has a low ignition temperature and explosions of hydrogen fuels are more likely to occur.[248] An important but unexplored potential problem is leakage of hydrogen in an enclosed structure such as a garage in a home or a commercial structure. The garages used for the prototype hydrogen vehicles in California have hydrogen sensors on their ceilings and a duct system to pull in outside air if the sensors detect a hydrogen leak.[249] Because of the potential for an explosion, insurance costs are likely to be high enough to be a serious deterrent to the sale and use of hydrogen. Hydrogen use could be considered an abnormally dangerous activity, which could affect insurance availability and cost.[250] Some of DOE's reports seem to place a greater emphasis on "public education" as the remedy to the "perception that hydrogen is explosive and unsafe," as though public prejudice, and not safety, is the obstacle limiting hydrogen use.[251] Whether hydrogen is more or less dangerous than gasoline, it is different. To use hydrogen will require new safety codes, building codes, zoning changes, and other legal changes necessary to the creation of a new infrastructure.

B. Cost

Today, hydrogen at the point of use is more expensive than gasoline with equivalent energy content. The current cost of hydrogen fuel is $5 per kg; the goal is $1.50 per kg[252] (a kg of hydrogen is comparable in energy to a gallon of gasoline).[253] Hydrogen, however, is projected to be equivalent to gasoline in cost per mile traveled when used in a fuel cell vehicle with its higher fuel efficiency, if produced from an advanced coal-burning electric power plant producing both electricity and hydrogen.[254] The ultimate goal is for hydrogen to be less costly than present fuels because of electrolysis improvements, as well as advances in solar and wind production used to produce the needed electricity.[255] Until then, most hydrogen will be produced from natural gas, which has had major price increases and can be expected to continue to increase in price.[256]

Automotive fuel cells cost $1,500 to $10,000 per kw which must be reduced to $50 to $100 per kw to be competi-

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[236] U.S. DOE, *Safety, Codes & Standards: The Hindenburg Myth*, *at* http://www.eere.energy.gov/hydrogenandfuelcells/codes/safety-feature,html (last visited Apr. 20, 2004). Possibly none of the 35 fatalities were killed by the hydrogen fire. Burning diesel fuel, flamable furnishings, and jumping from the dirigible caused the fatalities. Twenty-seven of 35 fatalities were due to jumping from the aircraft. Sixty-two survivors rode the burning Hidenburg to the ground while the hydrogen burned above them. *See* Lambert, *supra* note 59, at 35; *see also* Davis et al., *supra* note 97, at 21.

[237] *Hydrogen Economy Hearings*, *supra* note 19, at 45 (prepared statement of J. Byron McCormick, Executive Director, Fuel Cell Activities, GM). GM was arguing to delist hydrogen as a hazardous substance and list it as a fuel. *Id.*

[238] THE KEYS TO THE CAR, *supra* note 14, at 68.

[239] U.S. DOE, DRAFT, MULTI-YEAR RESEARCH, DEVELOPMENT, AND DEMONSTRATION PLAN, TECHNICAL PLAN-HYDROGEN SAFETY 3-120 (2003) [hereinafter U.S. DOE, HYDROGEN SAFETY]. The DOE report never mentions the possibility of explosions from hydrogen.

[240] THE KEYS TO THE CAR, *supra* note 14, at 68.

[241] *Id.* at 68.

[242] THE HYDROGEN ECONOMY, *supra* note 27, at xix.

[243] *California's AB 1493: Trendsetting or Setting Ourselves Up to Fail?*, 21 UCLA J. ENVTL. L. & POL'Y 97, 123-24 (2002/2003).

[244] Davis et al., *supra* note 97, at 21.

[245] Moy, *supra* note 117, at 349.

[246] *Id.* at 355.

[247] *Id.*

[248] *Id.* at 356.

[249] Ball, *supra* note 7.

[250] Moy, *supra* note 117, at 349.

[251] *The Hydrogen Fuel Infrastructure*, *supra* note 15, at 66.

[252] *See* MULTI-YEAR RESEARCH HYDROGEN PRODUCTION, *supra* note 22, at 3-8.

[253] CALIFORNIA CLEAN FUELS, *supra* note 93, at 4.6.

[254] *NRC Report Cites Prime Hydrogen Role for Coal*, CLEAN COAL TODAY, Spring 2004, at 10.

[255] THE HYDROGEN ECONOMY, *supra* note 27, at xxi.

[256] THE HYPE ABOUT HYDROGEN, *supra* note 39, at 43.

tive.[257] Fuel cells have been successfully used in the space program for many years where cutting edge technology is pursued regardless of cost. The price of hydrogen fuel cells is exacerbated by the fact that the catalyst used in the PEM fuel cell is the expensive metal platinum. PEM fuel cells use a platinum electrocatalyst of up to several grams.[258] One study has indicated the cost of platinum is $57 per kw, which is higher than the cost target for the entire fuel cell system of the FreedomCAR program.[259] Research to find cheaper catalysts for fuel cells suitable for motor vehicles has not yet been successful. PAFCs, used in stationary source applications, might be competitively priced if a substantial market existed. But without such a market, the price remains high.[260]

R&D costs to make hydrogen a viable fuel will be high for every aspect of the hydrogen economy. There are cost barriers (often tied to technical barriers) for the various technologies that can be used to produce hydrogen.[261] The infrastructure to deliver and use hydrogen is not in place; new pipeline systems may have to be created. New materials may be required to make the pipelines. It is considered less expensive to produce hydrogen in decentralized locations near the point of use than to develop the infrastructure to deliver hydrogen from large centralized production facilities. Nevertheless, hydrogen fueling stations are costly to build; there is speculation that they could cost over $1 million per station.[262] To outfit an existing gas station with the equipment to convert natural gas to hydrogen would cost about $400,000.[263]

While the costs of fuel cell technology remain high, government policies support the continued reliance on existing technologies.[264] For mobile sources, gasoline taxes in the United States are one-third to one-half what they are in Japan and Europe. Motor vehicles have substantially reduced emissions, and hybrid engines and ultra-low emission vehicles have the potential for further reduction at lower costs than fuel cell vehicles. For stationary sources, environmental laws make electric power production from old coal-burning power plants attractive.[265] Government subsidies for deploying clean energy technologies are granted in Japan and Europe, but are more limited in the United States.[266] There are no current federal restrictions on CO_2 emissions.[267] CO_2 trading systems that are beginning in Europe may make clean technologies a more attractive investment, but they are not part of the U.S. legal regime.[268] Moreover, there are proven existing technologies for generating electricity, such as gas turbines, reciprocating engines, and steam turbines that cost much less than fuel cells.[269] In addition, existing electric utilities are skilled at imposing regulatory barriers, fees, interconnection charges, and insurance requirements designed to increase costs for those seeking to use fuel cells.[270]

C. Consumer Acceptance

For nearly a century, the automobile and its supporting infrastructure has evolved. Today about 125,000 gas stations are available in the United States to provide fuel delivered from a worldwide network of oil wells, refineries, and delivery systems. This system establishes the consumer expectations that the Hydrogen Fuel Initiative expects to be met for hydrogen in 12 years.[271] Consumers will be reluctant to use a new fuel unless it is as convenient, cheap, and as safe to dispense as gasoline, but current performance of the technology for hydrogen production, storage, and use will not meet these expectations.[272]

The desire for a cleaner environment has led to an interest in hydrogen, but for the majority of consumers, a fuel's low cost and ease of use are the main concerns. Hydrogen now is neither inexpensive nor easy to use. To date, there is "no high-volume market for high-purity hydrogen."[273]

Moreover, there are no hydrogen fuel standards to assure consumers they are purchasing fuel that is free of impurities, e.g., sulfur.[274] Without the savings that economies of scale can bring, the cost of hydrogen will remain high.[275] Some of the companies that testified before Congress on the hydrogen economy mentioned how much easier the infrastructure development would be to implement if hydrogen use was widespread.[276] This is the "chicken and egg" problem that is often part of developing new technologies.[277]

In 2002, there were only seven hydrogen refueling sites in the United States; one was in Arizona, five were in California, and one was in Nevada.[278] In 2004, 12 hydrogen fueling stations are operating in California, and Gov. Arnold Schwarzenegger (R) plans to have 150 to 200 open by 2010.[279] Oil companies believe that to get consumers to buy hydrogen-fueled vehicles will require that about 30% of the 180,000 gas stations in the United States sell hydrogen.[280] California has about 140 natural gas stations open to the public, and this appears to be inadequate to make natural

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[257] Davis et al., *supra* note 97, at 7.

[258] OSWER REPORT, *supra* note 23, at 7.

[259] Davis et al., *supra* note 97, at 7.

[260] THE HYPE ABOUT HYDROGEN, *supra* note 39, at 36.

[261] *See* MULTI-YEAR RESEARCH HYDROGEN PRODUCTION, *supra* note 22, at 3-17 to 3-21.

[262] *California's AB 1493: Trendsetting or Setting Ourselves Up to Fail?*, 21 UCLA J. ENVTL. L. & POL'Y 97, 123 (2002/2003).

[263] Ball, *supra* note 7.

[264] THE HYPE ABOUT HYDROGEN, *supra* note 39, at 36.

[265] *See generally* Arnold W. Reitze Jr., *New Source Review: Should It Survive*?, 34 ELR 10673 (July 2004).

[266] The federal government offers a $1,000/kw subsidy for fuel cell purchase. New Jersey, Connecticut, and California offer subsidies as well. THE HYPE ABOUT HYDROGEN, *supra* note 39, at 54.

[267] *See* CAL. CODE REGS. tit. 13, §§1956.1, 1960.1, 1961. *See also* http://www.arb.ca.gov/msprog./ccvl/ccvl.htm (last visited June 16, 2004).

[268] THE HYPE ABOUT HYDROGEN, *supra* note 39, at 32.

[269] *Id.* at 60.

[270] *Id.* at 64 (citing NATIONAL RENEWABLE ENERGY LABORATORY MAKING CONNECTIONS: CASE STUDIES OF INTERCONNECTION BARRIERS AND THEIR IMPACT ON DISTRIBUTED POWER PROJECTS (2000)).

[271] THE HYDROGEN INITIATIVE, *supra* note 33, at 4.

[272] HYDROGEN ENERGY ROADMAP, *supra* note 26, at 14.

[273] *See* MULTI-YEAR HYDROGEN PRODUCTION, *supra* note 22, at 3-21.

[274] CALIFORNIA CLEAN FUELS, *supra* note 93, at 4.6.

[275] HYDROGEN ENERGY ROADMAP, *supra* note 26, at 19, 25.

[276] *Hydrogen Economy Hearings*, *supra* note 19, at 64.

[277] *See* Anair, *supra* note 131.

[278] DAVID & DIEGEL, *supra* note 6, at 6-6, tbl. 6.4.

[279] Carolyn Whetzel, *Schwarzenegger Signs Order to Create Partnership for Hydrogen Fueling Network*, 35 Env't Rep. (BNA) 904 (Apr. 23, 2004).

[280] Ball, *supra* note 7.

gas-powered vehicles attractive to the public.[281] In addition to few hydrogen stations, hydrogen fueling of motor vehicles is slow and difficult and cannot be done with the speed and ease demanded by consumers.[282] However, there have been some successful fueling station demonstrations, one by the Chicago Transit Authority using a high pressure "reciprocating liquid pump"; another was an "energy station" project that began in Las Vegas, Nevada, in September 2002.[283] Refueling infrastructure limitations would be eased by an evolutionary development of hydrogen vehicles where fleet applications that could be centrally fueled were converted to fuel cell vehicles and, subsequently, fuel cell vehicles were produced for commuter cars in urban areas.

Hydrogen's potential for leaks and explosions mandate extensive safety precautions, which consumers are unlikely to accept unless there is no other option. Insurance costs for those using hydrogen fuels and fuel cells also may be high. Citizen support of a hydrogen economy, therefore, is unlikely to materialize in the foreseeable future.

D. Competing Fuels and Technologies

Methanol, ethanol, biodiesel, and other fuels may work better and be more successful at replacing conventional gasoline and diesel fuel when petroleum becomes more expensive than it is today due to scarcity of supply. Government funding will not give hydrogen the boost it needs to be commercially successful if another fuel is cheaper, safer, and easier for the average person to use.

Hybrid technologies are particularly promising, especially for use in motor vehicles.[284] GM, as mentioned above, devotes part of its hydrogen fuel cell research to hydrogen hybrids, but electric/gasoline hybrids are more advanced, and they already are on the market. Electric/gasoline hybrid vehicles will be competitors in the near future with hydrogen fuel cell vehicles.[285] The Toyota Pruis has nearly the efficiency fuel cell vehicles are expected to attain, and hybrid diesel-electric vehicles are projected to be as efficient as a fuel cell vehicle.[286] As long as gasoline-powered cars are cost-competitive, the superior range of such conventional automobiles makes it very difficult for hydrogen-powered cars to compete.[287] At the end of 2002, hydrogen-powered vehicles had a 200-250 mile range and gasoline vehicles had a 380-400 mile range.[288] In addition, there is likely to be a lag effect even after hydrogen cars are otherwise competitive as many people will be highly reluctant to give up using a gasoline-powered vehicle as long as its fuel is affordable.

E. Ability to Reduce Dependence on Foreign Oil

Approximately two-thirds of the 20 million barrels of petroleum used daily in the United States is consumed by the transportation sector.[289] Increasing fuel efficiency and diversifying the sources of oil could help, but neither offers a long-term solution to reducing the nation's dependence on foreign oil.[290] The Hydrogen Fuel Initiative envisions hydrogen being commercially used in transportation by 2020, but this cannot be accomplished without a major improvement in the relevant technology.[291]

Some members of Congress are concerned that the president's claim that hydrogen would reduce U.S. dependence on foreign oil is baseless.[292] Rep. Henry Waxman (D-Cal.) has contended that DOE's studies do not support the president's contention.[293] The rate at which hydrogen vehicles could be added to the nation's vehicle fleet would not catch up with the rising demand for oil, due to increases in vehicle miles traveled and the decline in vehicle fuel efficiency. If we continue to be dependent on oil, we will remain hostages to the problems of the Middle East and to other potentially unstable regions of the world. Very little domestic oil remains; the amount likely to be found in Alaska is disputed, but the supply is too small to seriously affect the nation's need of foreign oil. DOE predicts that approximately 40 million tons of hydrogen per year will be required in the hydrogen economy, enough to power 25 million homes or 100 million cars.[294] This is the current worldwide production.[295] If natural gas is used to produce hydrogen and the increased demand for natural gas is satisfied by using imported natural gas, there would be little, if any, reduction in total energy imports.[296]

F. Environmental Impacts of a Hydrogen-Based Economy

The environmental benefits of a hydrogen-based economy cited by many proponents seem too good to be true. They assert that hydrogen when combusted produces only water and heat.[297] Hydrogen used in a fuel cell produces electricity and water. It is true that hydrogen has the potential for providing our energy-dependent society with a pollution-free source of power that also has no GHG emissions. But the actual impacts on the environment of widespread hydrogen production and use are unknown. While combusting hydrogen produces only water as a byproduct, the common hydrogen-producing technologies usually involve the conversion of fossil fuels that can result in adverse environmental impacts.[298]

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[281] *Id.*

[282] *The Hydrogen Fuel Infrastructure, supra* note 15, at 68.

[283] *Id.*

[284] Sheila Schimpf, *As Hybrids Gain in Popularity, More Models Planned in Coming Years, Auto Officials Say*, 35 Env't Rep. (BNA) 58 (Jan. 9, 2004).

[285] Hydrogen Energy Roadmap, *supra* note 26, at 31.

[286] The Hype About Hydrogen, *supra* note 39, at 7.

[287] *Id.*

[288] *Id.*

[289] David & Diegel, *supra* note 6, at 1-1. U.S. transportation petroleum use in 2002 was 161.9% of the domestic petroleum production. *Id.*

[290] The Hydrogen Initiative, *supra* note 33, at 2.

[291] *Id.* at 3.

[292] *Bush Fuel Cell Plan Would Increase Burden on EPA Waste Programs*, Inside EPA Wkly. Rep., Oct. 1, 2003, at 3.

[293] *Id.*

[294] Hydrogen Energy Roadmap, *supra* note 26, at 11.

[295] *Hydrogen Economy Hearings, supra* note 19, at 57. The U.S. consumes about 20% of the world's hydrogen. David & Diegel, *supra* note 6, at 6-12 tbl. 6.8.

[296] The Hydrogen Economy, *supra* note 27, at xvi.

[297] NO_x, which are pollutants associated with combustion, are created primarily from the oxidation of the nitrogen, present in air, at high temperature. To prevent NO_x formation requires the temperature of combustion be kept below the level at which NO_x is created.

[298] Multi-Year Research Plan, *supra* note 4, at I; Multi-Year, Program Benefits *supra* note 8, at 2-6. About 60% of people in the United States "live in areas where levels of one or more air pollutants are high enough to affect public health and/or the environment." *Id.*

Hydrogen does have a start-to-finish efficiency dilemma; it takes more energy to produce hydrogen than is provided by the hydrogen that is the end product. This net energy loss is further compounded if the hydrogen has to be frozen or compressed for storage and transport and then re-heated or decompressed for use. This means that at least in the short term a hydrogen-based economy may increase the use of fossil fuels. Many of the cleaner sources of hydrogen, especially natural gas, might better be used directly instead of going through the expensive, energy-consuming conversion to hydrogen. The argument for conversion to hydrogen is the versatility of the fuel, but this may not make hydrogen a rational choice over the direct use of clean sources of energy in the near term. In the long term, if we are to maintain a high standard of living in the post-petroleum age, a hydrogen-based economy is an alternative that should be considered. Using renewable energy to produce hydrogen through electrolysis of water or by processing coal while sequestering CO_2 are technologies that may be environmentally acceptable. However, these approaches have numerous technical and economic obstacles to overcome if they are to become commercially accepted. More importantly, a serious hydrogen R&D program may lead to technology advances that provide options that are not available today.

1. Potential Climate Effects

Hydrogen production is expected to increase the emissions of the GHG, CO_2, if hydrogen is produced using coal, oil, or natural gas unless the CO_2 that is a byproduct is sequestered. Sequestration in geologic formations is the principal approach being considered because of the abundance of potential storage sites in depleted oil reservoirs, unmineable coal seams, and saline formations.[299] However, we have little knowledge of whether sequestration will be effective for the long time periods required. Even losses as small as 1% per year, while difficult to detect, could make sequestration a costly failure.[300] Thus, monitoring sequestration efforts and the ability to have continuing meaningful oversight of stored CO_2 is a necessary part of a sequestration program.

DOE's FutureGen project is focused on developing cost-effective sequestration technology, which does not currently exist and may be difficult to achieve.[301] The cost of CO_2 sequestration will be reflected in the cost of hydrogen and may cost $1,000 per ton of carbon removed. In contrast, reducing CO_2 emissions by 50% from the electric power industry is estimated to cost between $75 and $150 per ton of carbon removed.[302] If hydrogen is produced using renewable sources of electric power or nuclear power, no CO_2 is released. But, as previously discussed, this approach to the generation of hydrogen is unlikely to be used in the foreseeable future. If high-temperature fuel cells are used at stationary sources and their waste heat is utilized, overall CO_2 savings may be significant, depending on the alternative process to which it is compared. However, the low temperature fuel cells used for mobile source applications, may not result in meaningful CO_2 emission reductions when compared with "clean vehicles."[303] According to DOE, a typical vehicle emits 374 grams of GHG per mile traveled. If the hydrogen fuel is produced by grid electricity without sequestration of CO_2, the figure increases to 436 grams. If fuel cell vehicles use hydrogen produced by steam reforming of natural gas, emissions drop to 145 grams because the increased efficiency of fuels cells compared to internal combustion engines helps offset the emissions attributable to the conversion of fossil fuel into hydrogen.[304] However, much of the benefit of hydrogen fuel on GHG emissions also can be obtained by using existing motor vehicle technology. Natural gas-fueled vehicles emit 310 grams per mile, and hybrid electric vehicles fueled with natural gas have GHG emissions of 177 grams per mile.[305] To control the nation's carbon emissions requires dealing with motor vehicles because they accounted for 32.8% of U.S. carbon emissions in 2001, although light-duty vehicles contribute only about 20%.[306] The transportation sector has been responsible for nearly one-third of U.S. carbon emissions for more than a decade,[307] but the transportation sector is expected to contribute one-half of the increase in the U.S. CO_2 emissions projected for 2025.[308]

CO_2 releases can be more effectively controlled by reducing the amount of fossil fuel combusted; for motor vehicles this means increasing vehicle miles traveled per unit of fuel. The Bush Administration's Global Climate Change Initiative calls for an 18% reduction by 2012 in carbon intensity, which is the ratio of GHG emissions to economic output.[309] Such a reduction, even if achieved, will not prevent increased atmospheric CO_2 concentrations because global CO_2 emissions appear to require reduction by an order of magnitude in order to stabilize atmospheric CO_2 concentrations.[310] CO_2 emissions will need to be controlled from both mobile and stationary sources regardless of efficiency improvements.[311]

The use of hydrogen also is likely to result in an increase in the amount of molecular hydrogen (H_2) released into the atmosphere. About one-half the hydrogen in the atmosphere is produced by photochemical oxidation of methane and other hydrocarbons, and one-half comes from biogenic processes and combustion. One-quarter of the total emissions is associated with human activities.[312]

Hydrogen is an indirect GHG that reacts with the hydroxyl radical (OH) in the atmosphere and with soil micro-

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[299] *Id.*

[300] The Hype About Hydrogen, *supra* note 39, at 166.

[301] *Hydrogen Economy Hearings*, *supra* note 19, at 32 (testimony of Hon. David K. Gorman, Ass't Secretary for Energy Efficiency and Renewable Energy, U.S. DOE).

[302] David W. Keith & Alexander E. Farrell, *Rethinking Hydrogen Cars*, 301 Science 315 (2003).

[303] The Hype About Hydrogen, *supra* note 39, at 59.

[304] *See Well-to-Wheels Analysis*, *supra* note 72, at 5.

[305] Matthew L. Wald, *Will Hydrogen Clear the Air? Maybe Not, Say Some*, N.Y. Times, Nov. 11, 2003, at C1.

[306] David & Diegel, *supra* note 6, at 11-1; U.S. EPA, *Light-Duty Automotive Technology and Fuel Economy Trends: 1975 Through 2004*, *at* http://www.epa.gov/otaq/fetrends.htm (last visited June 16, 2004).

[307] David & Diegel, *supra* note 6, at 11-5, tbl. 11.4.

[308] U.S. DOE, Energy Information Administration, Annual Energy Outlook 2003, tbl. A19 (2003).

[309] *Carbon Sequestration Program Explores Options*, Clean Coal Today, Spring 2004, at 6.

[310] Keith & Farrell, *supra* note 302, at 316.

[311] GHG emissions in the United States increased 13% during 1990-2002. *Greenhouse Gases Increased 13 Percent From 1990 to 2002, According to EPA*, 35 Env't Rep. (BNA) 986 (May 7, 2004).

[312] *Id.* at 582.

organisms. The reactions in the atmosphere increase the GHG, methane, but the effect of hydrogen emissions on the soil sink is unknown.[313] H_2 is, after methane, the most abundant atmospheric trace gas. The effect of increased hydrogen releases from human activities on the atmosphere's ratio of trace gases or on the ratio of deuterium to hydrogen is largely unknown.[314] To complicate matters, the effects of hydrogen releases on the atmosphere vary with elevation.[315] Experience with natural gas indicates that leakage of hydrogen will occur, and as the hydrogen economy develops, it should be anticipated that a small percent of the fuel will be added to the environment.[316] The losses could be more significant from refueling, depending on the form in which hydrogen is delivered to a vehicle.[317] While the environmental effects will be a function of the amount of hydrogen released, leakage rates, are unknown. They could be as high as10-20%, with 3% a more probable estimate, but perhaps a loss rate of less than 1% could be achieved.[318]

The dispersion of hydrogen into the atmosphere might not be as destructive to the biosphere as the addition of water to the stratosphere that is formed when escaping hydrogen reacts with oxygen.[319] One recent study contends that the resultant increase in water in the atmosphere would lead to *cooler* stratospheric temperatures, and the ice crystals in the stratosphere would deplete ozone.[320] Critics of the study contend that its conclusions "represent unlikely extreme cases that are not well connected to current or likely future levels of hydrogen usage or system leakage."[321]

Overall, the long-term impacts of a hydrogen release on the environment are essentially unknown; some contend hydrogen is environmentally safe; others worry its production could be environmentally destructive.

2. Stationary Source Impacts

The standard current process for producing hydrogen is to use SMR which is a multi-step process. Natural gas (CH_4) reacts with water vapor under high pressure and temperature in the presence of a catalyst (usually nickel) to form CO and hydrogen. In the second stage, called the water-gas shift, CO is exposed to steam to produce CO_2 and hydrogen. The flue gas is now 70-80% hydrogen plus CO_2, CH_4, water vapor, and CO. In the third stage, PSA is used to separate the hydrogen and the remaining gases are vented to the atmosphere as air pollutants and GHGs.[322]

The process used to produce hydrogen will affect the type and quantity of emissions released into the atmosphere. However, there is little evidence that producing hydrogen from existing industrial processes produces pollutants that are not routinely handled by industry.

If increased supplies of hydrogen are to be produced from natural gas, natural gas demand will increase. Natural gas prices already have increased substantially because of the increased demand for this fuel from electric power plants.[323] A hydrogen-based economy could put additional upward pressure on natural gas prices.

A major effort to develop new natural gas supplies also could be expected to result in increased drilling with its associated adverse environmental impacts. One important pollution problem relates to the disposal of "produced water." For example, coalbed natural gas developers in Montana and Wyoming are opposing the more stringent water pollution control requirements that are pending.[324] If more natural gas is produced and used there will be more small leaks of this fuel to the environment. Methane, the primary constituent of natural gas, has 21 times the global warming effect of CO_2.[325]

Hydrogen also can be produced from coal using the water-gas shift reaction used for conversion of natural gas. This process is the focus of DOE's FutureGen program, discussed earlier. The use of coal for hydrogen production will depend on technical and cost reduction advances. The most important unresolved problem is whether effective long-term carbon sequestration can be accomplished on a large scale in a manner that is economical and practical.

In addition, water can be used to produce hydrogen through electrolysis using electricity generated by fossil fuels or nuclear power. Since the conversion process is about 70% efficient and electric generation is about 30% efficient, the overall efficiency is about 20% (.7 x .3). Thus only one-fifth of the primary energy remains available in the hydrogen.[326] All of the environmental problems created by the electric power industry would be part of the hydrogen production process.[327] To replace the gasoline sold in the United States with hydrogen produced by electrolysis would require more electricity than is sold in the nation today.[328]

Environmentalists and many industry representatives want to encourage the production of hydrogen by electrolysis using renewable sources of electricity. At this time, wind power is the most developed and least costly method of producing power from renewable sources. But today, this source of electricity produces less than 1% of the nation's electricity.[329] To produce a kg of hydrogen requires 9 kg of water. The 40 million tons per year of hydrogen, which is the

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[313] *Id.*

[314] Thom Rahn et al., *Extreme Deuterium Enrichment in Stratospheric Hydrogen and the Global Atmospheric Budget of H_2*, 424 NATURE 918 (2003). Deuterium, also known as heavy hydrogen, is an isotope of hydrogen having twice the mass or ordinary hydrogen.

[315] *Id.*

[316] Michael J. Prather, *An Environmental Experiment With H_2?*, 302 SCIENCE 581 (2003).

[317] THE HYPE ABOUT HYDROGEN, *supra* note 39, at 94.

[318] Martin G. Schultz et al., *Air Pollution and Climate-Forcing Impacts of a Global Hydrogen Economy*, 302 SCIENCE 624 (2003).

[319] Tracey K. Tromp et al., *Potential Environmental Impact of a Hydrogen Economy on the Stratosphere*, 300 SCIENCE 1740, 1741 (2003).

[320] *Id.*

[321] Daniel M. Kammen & Timothy E. Lipman, *Assessing the Future Hydrogen Economy*, 302 SCIENCE 226 (2003).

[322] THE HYPE ABOUT HYDROGEN, *supra* note 39, at 73.

[323] *See Testimony Before House Committee on Energy and Commerce* (June 10, 2003) (statement of Alan Greenspan, Federal Reserve), *available at* www.federalreserve.gov/boarddocs/testimony/2003/20030610/default.htm (last visited June 16, 2004); Mike Ferullo, *Increased Domestic Drilling Recommended to Reduce Record Prices for Natural Gas*, 35 Env't Rep. (BNA) 722 (Apr. 2, 2004).

[324] *Tribe's Role in Powder River Basin Hands EPA Tough Energy Choices*, INSIDE EPA WKLY. REP., May 26, 2004, at 23.

[325] THE HYPE ABOUT HYDROGEN, *supra* note 39, at 149.

[326] *Id.* at 75.

[327] *See generally* Arnold W. Reitze Jr., *State/Federal Command-and-Control Regulation of Emissions From Fossil Fuel Electric Power-Generating Plants*, 32 ENVTL. L. 369 (2002).

[328] THE HYPE ABOUT HYDROGEN, *supra* note 39, at 76.

[329] NATIONAL ENERGY POLICY DEVELOPMENT GROUP, NATIONAL ENERGY POLICY (2001). Wind energy accounts for 6% of the renewable electricity generation and 0.1% of the total electricity supply. *Id.* at 6.6

amount projected to be needed for an established hydrogen-based program in the United States, would require at least 360 million tons of water or 90 billion gallons.[330] Where will the water come from? If wind power from the Great Plains is to be used for hydrogen production, either electricity or hydrogen will have to be shipped from where the power is being generated to where it will be used. This will require major additional infrastructure.

Wind power also could be developed from offshore turbines; Denmark and the United Kingdom have pioneered this technology.[331] Although no offshore facilities currently exist in the United States, several proposals have been made to site wind-based facilities at East Coast sites. One major offshore wind energy proposal to develop a wind energy project in Nantucket Sound has been the subject of intense controversy and litigation by local interests.[332] The Nantucket opposition continues in court[333] and administratively with the U.S. Army Corps of Engineers (Corps).[334] The Corps expects to complete a draft environmental impact statement in mid-2004, and a final decision on the permit will not be made until 2005.[335] Expansion of wind or solar power electric-generating capacity, however, would produce more environmental benefits if it was used as a substitute for electricity generated from old coal-fired power plants, but this requires wind facilities to be located where that power can be sent to appropriate grids.[336]

Solar power can be used to produce hydrogen[337] in a manner that is nonpolluting and low in operating costs. Moreover, the energy source is inexhaustible. But, the capital costs are high for the existing technology needed to produce hydrogen using photovoltaic energy.[338] Because of the number of technological breakthroughs needed, it is difficult to predict when cost-effective solar technology will be available. At this time, solar energy accounts for about 0.02% of the electricity generated in the United States.[339] A World Resources Institute presentation noted that use of photovoltaics to supply the U.S. economy would require 164,000 square miles of land, an area larger than the state of California.[340]

The cost of reducing conventional pollutants from motor vehicles by using hydrogen fuel will be high. The reason is that gasoline-powered automobiles have been improved to comply with air pollution requirements so that their emissions per unit of energy utilized is very low compared to other industrial sectors or to other transportation modes.[341] Continuous improvement in motor vehicle emissions is expected to continue. Therefore, the benefits, in terms of reduced air emissions from a hydrogen-based transportation sector, will be low when compared with costs. For example, nitrogen oxide (NO_x) reductions from mobile sources using hydrogen will cost about $1 million per ton of NO_x, but EPA's Tier 2 standards are projected to cost $2,000 to eliminate a ton of NO_x.[342] Inspection and maintenance programs will cost about $4,000 per ton and programs to scrap old vehicles cost about $10,000 per ton of NO_x.[343] NO_x control from electric power production also has costs in the $10,000 per ton range.[344] Thus, hydrogen vehicles are a costly way to reduce NO_x but they would benefit the environment by not having a small portion of the vehicle fleet producing high emissions, which occurs with gasoline-powered vehicles.[345]

Many general descriptions of hydrogen fuel cells state that pure water is the only byproduct created by fuel cell use. However, according to a spokesman from the University of California, that is not quite true.[346] Fuel cells also can emit a small amount of nitric oxide, which is a precursor to photochemical oxidants, and a fuel cell also gives off the products of the degradation of the fuel cell stack.[347] If fuel cells are produced using nanotechnology, the environmental impacts are largely unknown.[348] Fuel cells that create their needed hydrogen from onboard reformation of gasoline, natural gas, or methanol would present additional environmental problems, but the use of such fuel cells do not appear to be likely at this time.

Perhaps the most significant role for environmental law to encourage the use of renewable technology in general and hydrogen fuel cells in particular would be to make emission requirements for existing facilities more stringent and siting problems for facilities using existing technologies difficult to overcome. This approach would help make nonpolluting technologies more attractive. The CAA's new source review program makes it a challenge to site new major sources in areas that do not meet NAAQS. Proposals to further reduce the level of emission caps for sulfur dioxide and NO_x further enhance the attractiveness of nonpolluting energy sources.[349] If fuel cells are to be part of the solution to urban air pollution, their most promising applications involve stationary power sources in nonattainment areas where fuel

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[330] The atomic weight of hydrogen is 1.0079, for oxygen it is 15.9994, therefore, water (H_2O) has an atomic weight of 18.0152. Water is nine times heavier than its hydrogen component.

[331] Michael Schulz, *Questions Blowing in the Wind: The Development of Offshore Wind as a Renewable Source of Energy in the United States*, 38 New Eng. L. Rev. 415, 418 (2004).

[332] *See* Alliance to Protect Nantucket Sound v. Department of the Army, 288 F. Supp. 2d 64 (D. Mass. 2003); The Alliance to Protect Nantucket Sound, *The Worst Location*, *at* http://www.saveoursound.org/bestworst.html (last visited May 26, 2004).

[333] Alliance to Protect Nantucket Sound v. Department of the Army, No. 03-2604 (1st Cir. 2003).

[334] The opponents argue that the wind project will threaten wildlife, impede navigation, discourage tourism, and be aesthetically unpleasing. While these environmental concerns are site-specific, it would be reasonable to expect "not in my backyard" opponents to emerge for some substantial projects.

[335] U.S. Army Corps of Engineers, *Fact Sheet*, *at* http:www.nae.usace.army.mil/projects/ma/ccwf/farmfact.pdf (last visited May 26, 2004).

[336] *Id.*

[337] Multi-Year Program Benefits, *supra* note 8, at 2-10, 2-11.

[338] *Id.* at 3-5.

[339] National Energy Policy, *supra* note 329, at 6-7.

[340] IPHE Ministerial Meeting, Washington, D.C., Nov. 19, 2003, Jonathan Pershing and Jim MacKenzie, Energy and Pollution Program, World Resources Institute.

[341] Keith & Farrell, *supra* note 302.

[342] *Id.*

[343] *Id.*

[344] *Id.*

[345] *Id.*

[346] *Hydrogen Economy Hearings*, *supra* note 19, at 68 (prepared statement of Scott Samuelson, Director, National Fuel Cell Center, University of California).

[347] *Id.*

[348] *See* Lynn L. Bergeson & Bethami Auerbach, *The Environmental Regulatory Implications of Nanotechnology*, 35 Env't Rep. (BNA) 840 (Apr. 16, 2004).

[349] *See generally* Arnold W. Reitze Jr., *State and Federal Command-and-Control Regulation of Emissions From Fossil-Fuel Electric Power-Generating Plants*, 32 Envtl. L. 369 (2002).

cells can achieve higher overall efficiency through cogeneration systems and can use less costly technology.[350]

3. Disposal and Recycling

EPA's Office of Solid Waste and Emergency Response (OSWER) is investigating the ramifications of fuel cell use[351] under the Resource Conservation and Recovery Act (RCRA) statute.[352] In a May 2003 report, the OSWER focused on PEM fuel cells because they are the closest to "widespread commercialization."[353] Used fuel cells contain components that are likely to be hazardous waste under RCRA based on their characteristics.[354] Some components that are too valuable to be discarded will be recycled.[355]

However, according to the OSWER, while reuse is the ideal option, this option is unlikely to occur in the near future for most components because of the rapid pace of technology change and the deterioration of materials used in fuel cells.[356] Recycling methods include manual separation of fuel cells, chemical recovery to electrochemically recover precious metals, and mechanical treatment, which involves shredding fuel cell parts and separating them based on density.[357] Disposal options include incineration and land disposal.[358] The OSWER report focused on the unique problems presented by the major components of the PEM fuel cell: the proton exchange membrane (8% of the fuel cell by weight); the electrocatalysts (less than 7% of the fuel cell by weight); and the bipolar plate (77% of the fuel cell by weight).[359]

The proton exchange membrane cannot be reused because it becomes contaminated and dehydrated in use.[360] Recycling the fluorine-containing polymer membranes (the most commonly used substance is called nafion) would involve chemical extraction of the membrane from its position between the electrodes, and a method to accomplish this has not yet been developed.[361] Incineration is not a useful option because the membranes contain hydrogen fluoride, and management of the combustion byproducts would be difficult.[362]

The electrocatalysts are made of platinum and platinum-group metals, and they are recycled because these metals are expensive.[363] The chemical process used to recover platinum and ruthenium (a platinum group metal commonly used in fuel cells) already has been developed and is less environmentally damaging than primary production of platinum.[364] The high cost of platinum drives the search for alternative catalyst materials.[365]

Bipolar plates, which make up most of the weight of the fuel cell, may be best disposed of through incineration due to the toxicity of the recycling process and because the composition of the plates is changing as new technology develops.[366] Graphite, carbon, and steel are current options for plate composition; steel is the easiest to clean and reuse or recycle.[367] The remaining components of the fuel cells may have to be disposed of as hazardous waste, including newly developed materials that are present in fuel cells about which the OSWER knows little. The OSWER has concluded that disposal of fuel cell materials will be very complicated.[368]

Chemical hydride fuel cells store hydrogen more efficiently than processes that depend on using hydrogen in the form of a compressed gas or cryogenic liquid. Chemical hydride fuel cells produce hydrogen by catalyzing solutions of chemicals that may produce hazardous byproducts. RCRA requirements could hamper chemical hydride fuel cell development, according to at least one manufacturer. Other companies believe that chemicals can be selected that will not create wastes that are hazardous under RCRA.[369]

VII. Conclusion

There are a wide range of views about the prospects and timing of the introduction of fuel cells in passenger vehicles on a commercial scale. Optimists (especially the EERE) contend that vehicles could be available for sales by 2018, and we could have a hydrogen economy by 2040[370]; skeptics argue that 50 or more years will be required. Hydrogen technology has changed since the 1970s, but large-scale use will not occur without major breakthroughs in the technology.[371] There are significant cost and technology barriers to a full hydrogen economy, which, especially in the realm of storage, are not likely to be overcome soon. If hydrogen is to become a commercially used energy carrier, it will probably develop first for stationary source applications. Its use in motor vehicles can be expected to first appear in fleet vehicles and, subsequently, in commuter vehicles. Today, hydrogen is not a practical choice for motor vehicles and probably will not attain practicability by DOE's deadlines. Moreover, without controls on CO_2, either through limits on emissions or a tax on emissions, an important potential incentive to the development of a hydrogen-based economy does not exist.

Some critics have questioned why there is an emphasis on hydrogen but not on hybrid engine vehicles or other potentially cost-effective alternative technologies. The American Petroleum Institute has expressed concern in congressional hearings that they are wary of investing in the infrastructure and wary of the likelihood of the success of hydrogen tech-

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[350] THE HYPE ABOUT HYDROGEN, *supra* note 39, at 39.

[351] OSWER REPORT, *supra* note 23.

[352] RCRA is the common name for the Solid Waste Disposal Act, found at 42 U.S.C. §§6901-6992k, ELR STAT. RCRA §§1001-11011.

[353] OSWER REPORT, *supra* note 23, at 4.

[354] Characteristic wastes are those solid wastes that are ignitable, corrosive, reactive, or toxic as defined at 40 C.F.R. pt. 261, subpt. C (2003).

[355] OSWER REPORT, *supra* note 23, at 7.

[356] *Id.* at 8.

[357] *Id.*

[358] *Id.*

[359] *Id.* at 8-9.

[360] *Id.* at 9.

[361] *Id.*

[362] *Id.*

[363] *Id.*

[364] *Id.* at 10.

[365] *Id.*

[366] *Id.* at 11.

[367] *Id.*

[368] *Id.*

[369] *EPA Faces Growing Pressure to Exempt Hydrogen Fuel Cell Wastes*, INSIDE EPA WKLY. REP., May 26, 2004, at 6.

[370] *See* MULTI-YEAR RESEARCH PROGRAM BENEFITS, *supra* note 8, at 2-8.

[371] *California's AB 1493: Trendsetting or Setting Ourselves Up to Fail?*, 21 UCLA J. ENVTL. L. & POL'Y 97, 124 (2002/2003).

nologies.[372] For the next decade, advanced gasoline and clean diesel engines will deliver more benefits sooner than hydrogen or fuel cells.[373] Moreover, energy efficiency improvements have the potential for improving the environment and decreasing petroleum consumption more quickly than the Hydrogen Fuel Initiative, and as these improvements are commercialized the benefits of hydrogen fuel cells become less significant.

A well-to-wheels analysis, that evaluates the energy losses in producing hydrogen from various hydrocarbons, indicates the benefits of fuel cells when compared with other vehicle propulsion systems are modest. The energy required in Btus per mile are: 2,368 from a fuel cell vehicle using hydrogen derived from methane, and 2,867 from a compressed natural gas (CNG), spark-ignited, hybrid electric vehicle.[374] The fuel cell vehicle has the additional advantage of releasing only about one-eighth the CO_2 of a CNG vehicle, but only if CO_2 is sequestered in the hydrogen production process. Conventional pollutants released in producing the hydrogen may be higher than those released by the operation of the CNG vehicle.[375]

Since the release of the National Energy Policy in May 2001, DOE has increased its efforts to launch a workable hydrogen economy program to meet the goals identified by the Administration in the future (2010-2045).[376] However, much of the optimism at DOE about using hydrogen as a fuel is based on achieving substantial improvements in technology at every stage of hydrogen production and use. Hydrogen may play a role in meeting future energy needs, but a hydrogen economy may not be a realistic expectation.[377] Trying to jump-start the infrastructure needed for a hydrogen-based transportation system appears premature, but some industry proponents argue that infrastructure development can dramatically decrease the time required for consumer acceptance of fuel cell vehicles.[378]

The rush to a hydrogen economy by our political leadership appears to be occurring with inadequate analysis of energy, environmental, and economic issues. What is needed now is a serious open discussion concerning energy policy in general and alternatives to petroleum in particular. A thorough analysis of the costs and benefits of governmental efforts to develop the hydrogen economy should be prepared before we spend large sums on this technology to the exclusion of other, perhaps more promising, approaches.[379] Hydrogen-based systems should compete in the marketplace with existing energy systems that continue to improve and with other new systems, such as fuels produced at biomass plants, that may develop. It is undesirable to select hydrogen for special consideration without giving more attention to the full range of clean energy options. Governmental efforts should be limited to ensuring that existing and emerging technologies have an equal opportunity in the marketplace. Hydrogen should not be favored over other potential fuels, such as biofuels, by the premature infusion of large amounts of federal money. Moreover, federal and state funding should not be spent on hydrogen fuel development at the expense of programs aimed at near-term improvement in motor vehicle emissions or renewable energy technologies. A long-term program to develop a hydrogen economy must not be used to avoid the environmental and national security benefits that could be achieved quickly by combusting less fuel through improvements in fuel efficiency or through land use planning efforts.

The nation should pursue a balanced R&D program that includes hydrogen and non-hydrogen alternatives. R&D in hydrogen fuel cell technology, hydrogen storage, and distribution systems may increase our long-term transportation options, which will be important in the coming post-petroleum age. Moreover, federal funding of hydrogen research may be justified because the major benefits of this technology in terms of potential increased energy security, pollution reduction, and GHG reductions are benefits for the nation and are not benefits that the private sector realistically can recoup from investments that it makes.

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[372] *See Hydrogen Economy Hearings*, *supra* note 19, at 86-88 (prepared statement of the American Petroleum Institute).

[373] Sperling & Ogden, *supra* note 43, at 82.

[374] Davis et al., *supra* note 97, at 7.

[375] *Id.*

[376] *See* MULTI-YEAR RESEARCH INTRODUCTION, *supra* note 189, at 1-1, 1-3, and 1-9.

[377] One alternative fuel cell company representative testified at the House hearing that moving to a hydrogen economy will be more difficult than putting a man on the moon, and that "[w]e will never see a wholesale conversion at any point in time to a new fuel (hydrogen or otherwise)," but that it would take many types of alternative fuels to successfully reduce dependence on foreign oil and environmental pollution. *Hydrogen Economy Hearings*, *supra* note 19, at 54 (prepared statement of Catherine Rips, Sunline Transit Agency).

[378] Infrastructure development can shorten the time required to reach the "inflection point." This is the point where market forces take over and both energy and automotive sectors can achieve risk-adjusted returns that justify investment in a technology. DR. J. BYRON MCCORMICK, HYDROGEN "THE FIRST STEP" TRANSITION TO THE VEHICLES OF TOMORROW (2004).

[379] The analysis should be the equivalent of a programmatic environmental impact statement (EIS) under the National Environmental Policy Act (NEPA), although a programmatic EIS probably could not be mandated under existing law. The "deprivation of information" may be grounds for a federal court to find standing to challenge a government action. *See* Foundation on Economic Trends v. Watkins, 731 F. Supp. 530, 20 ELR 20724 (D.D.C. 1990). But, to have standing in a programmatic EIS case requires the plaintiff to challenge specific agency action in contrast to seeking an advisory opinion. The nature of the hydrogen program will make it difficult to meet the standing requirements. The courts are generally opposed to using the judiciary to decide national policy issues that should be left to the discretion of Congress. *See* Lujan v. National Wildlife Federation, 497 U.S. 871, 20 ELR 20962 (1990); Foundation on Economic Trends v. Lyng, 943 F.2d 79, 21 ELR 21439 (D.C. Cir. 1991); and Wilderness Society v. Griles, 824 F.2d 4, 17 ELR 21117 (D.C. Cir. 1987). Even if standing was recognized, the NEPA process does not apply to Congress or the president. 40 C.F.R. §1508.12 (2003). Legislative proposals from federal agencies to Congress are subject to programmatic EIS requirements, but proposals generated by Congress or the president are not. Moreover, legislative proposals subject to NEPA requirements do not include requests for appropriations. 40 C.F.R. §1508.17.