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Infrastructure Needs for the Hydrogen Economy

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Introduction

The Hydrogen Vision

The Hydrogen Economy is currently a hot item at the crossroads of government policy and technology. President George W. Bush announced in his 2003 State of the Union Address that the shift towards hydrogen fuel would "…make our air significantly cleaner, and our country much less dependent on foreign sources of energy."[1] In this speech the president introduced the Hydrogen Fuel Initiative (HFI) and proposed a $1.2 billion commitment to funding research for this project. In an address in Detroit on April 26, 2004, President Bush and Secretary of Energy Spencer Abraham publicized the first step towards this initiative with the funding of $350 million to be used for overcoming the many barriers hindering the national switch to the hydrogen economy.[2]

The obstacles that must be overcome in order for full integration of the hydrogen economy are numerous. There are many issues that must be addressed in order to safely and efficiently implement the use of hydrogen on a public level. In an address to the National Hydrogen Association on March 5, 2003, Secretary of Energy Spencer Abraham laid out four research challenges facing the prospect of implementing the hydrogen economy. These include[3]:

- Dramatically lowering the cost of fuel cells for transportation,
- Developing a diversity of sources for hydrogen production at energy costs comparable to gasoline,
- Finding viable methods of on-board storage of hydrogen for transportation uses, and
- Developing a safe and effective infrastructure for seamless delivery of hydrogen from production to storage to use.

Current Energy Methods

The driving force behind the United States government investing money in hydrogen research is the increasing demand for clean energy sources. The hydrogen economy has garnered worldwide attention as a possible long-term solution to the energy crisis that the world faces today. It is estimated that "the world's energy needs [will double] by the year 2050."[4] Our current sources of fuel are simply not sustainable for such a large

[1] President George W. Bush. 'State of the Union Address' January 28, 2003.
[2] Secretary of Energy Spencer Abraham. Detroit, Michigan. April 26, 2004.
[3] Secretary of Energy Spencer Abraham, address to the National Hydrogen Association March 5, 2003.
[4] Basic Research Needs for the Hydrogen Economy. May 13-15, 2003.

exigency. Also there is increasing pressure on fuel consumers to move towards a more environmentally friendly source of energy. With oil prices near $40 per barrel and gas prices over $2 per gallon, the United States needs to investigate its use of fossil fuels.

Fossil fuels are not a sustainable source of energy. Although supplies may be great, they are limited and will not be available forever. Currently the United States has only 3% of the world's oil reserves but uses nearly a quarter of those reserves. The United States relies heavily on foreign sources of oil; importing over half of the oil it uses everyday. If the United States continues along this trend, it is expected that by the year 2020 they will import 65% of their oil for daily consumption.[5] 85% of the energy supply in the U.S. is made up of fossil fuels. 39% of the national energy supply is from oil, 24% from natural gas, and 22% from coal.[6] Unfortunately, a good portion of the oil that the United States imports on a daily basis originates in the Middle East. Currently the United States has a very strong military presence in the Middle East and depending on that region for fuel significantly complicates our foreign policies.

Another problem with the United States' dependence on petroleum is the pollution associated with consumption. The burning of gasoline in automobiles releases green house gases that are believed to significantly contribute to global warming. Carbon dioxide accounts for "82% (weighted by global warming potential) of greenhouse gas emissions in the U.S."[7] It has cumulative hazardous effects on the atmosphere due to its lifetime of roughly 100 years. In addition oil releases toxic chemicals into the air such as NO_x, SO_x, and carbon monoxide. These chemicals polluting the air can have serious health effects and have been contributed to causing cancer to residents of metropolitan areas where air pollution is high and smog is prevalent.

Hydrogen Fuel

Why use Hydrogen for Fuel?

A fuel is something that can be consumed to produce usable work. Fuels are always high-energy substances; in order to be useful they must provide more energy than was used in the consumption process. All developed nations rely heavily on fuel to run everything that is powered by gasoline, coal, or electricity. Because hydrogen is the most abundant element in the universe and can be used for a fuel it makes sense for scientists and public officials to want to harness the energy of hydrogen.

Currently hydrogen is removed from hydrocarbons at oil refineries and chemical plants in processes such as the reforming of natural gas. The hydrogen is then collected by the plants and used onsite to produce other chemicals. Oil refineries typically use hydrogen to eliminate sulfur from fossil fuels such as diesel and gasoline.[8]

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[5] National Resources Defense Council. "Dangerous Addiction 2003." March 2003.
[6] Basic Research Needs for the Hydrogen Economy
[7] Basic Research Needs for the Hydrogen Economy
[8] Yacobucci, Brent D. and Curtright, Aimee E. *A Hydrogen Economy and Fuel Cells: An Overview*. CRS Report for Congress. RL32196. January 14, 2004.

In coming years, hydrogen could have pervasive uses as a fuel. It could be utilized as a fuel primarily in two methods. The gas could be burned directly in combustion engines. When coupled with oxygen, hydrogen could also be used in a fuel cell, a device that could be described as a chemical battery. Both of this means of using hydrogen as a fuel would create usable energy in the form of either motion or electricity but also both ways would spawn waste.[9]

Possible Production Methods of Hydrogen

Although hydrogen comprises roughly 75% of the known universe, it must be produced because it does not naturally exist in abundant quantities on earth. Unlike wind, sun, oil, and coal, hydrogen is not an energy source. Hydrogen is instead similar to gasoline and electricity in that it is an energy carrier. Energy carriers differ from energy sources in that they are simply ways to transmit useful energy to consumers.[10] There are many ways to derive hydrogen for fuel from other sources. Each method has both positive and negative affects attributed to it. The main areas to consider with the production of hydrogen are cost, power efficiency, sustainability, environmental effects, and public opinion.

Hydrogen can be produced through electrolysis: a process that uses electricity to split a water molecule. To create hydrogen in this manner an electric current is sent through the water, separating the hydrogen and oxygen. Two terminals are in the water. The hydrogen gas is attracted to the cathode and the oxygen gas is attracted to the anode. The gas bubbles up from the liquid towards air and is collected. The electricity to produce hydrogen "could come from solar cells, windmills, hydropower or safer, next-generation nuclear reactors."[11] Unfortunately these sources of energy are currently inefficient, expensive, unrealistic, or a combination of all three. Electrolysis is currently the most costly method of hydrogen production.

Another method of obtaining hydrogen is from coal-fired electricity. Obtaining energy from coal is most economical source in the majority of the nation. There are two drawbacks to this system. Although plentiful in the United States and abroad, coal is a non-renewable natural resource. Using coal to support the hydrogen economy is not a sustainable process. In addition, burning coal releases carbon dioxide into the atmosphere further contributing to global warming.

Hydrocarbons could be steam reformed to produce hydrogen. Methanol or natural gas could be used where it is first heated to vaporization in a combustion chamber. The fuel then moves to the steam reformed where a catalyst splits the fuel into many components including hydrogen. The mixture goes to a separation and purification chamber where the hydrogen is sent to a fuel cell and impurities are released in an exhaust stream. This

[9] U.S. Department of Energy, *Fuel Cell Report to Congress*. February 2003.
[10] Lovins, Amory B. *Twenty Hydrogen Myths.* Rocky Mountain Institute. June 20, 2003. pg 4
[11] Wald, Matthew L. *Questions about a Hydrogen Economy*. Scientific American. May 2004.

unfortunately is not the most efficient and environmentally friendly use of the raw materials that could be better utilized directly to produce power.

Safety Issues Concerning Hydrogen Production, Transportation, and Use

There are many safety issues that must be researched before hydrogen transportation systems plans are developed. Aspects that must be studied include but are not limited to "transport, kinetics, and hydrodynamics of hydrogen gas in enclosed structures and on its combustion properties, as well as the development of efficient and selective sensors for detecting hydrogen leaks."[12] In addition programs must be developed and implemented to provide information regarding the proper handling and care of hydrogen to the public and laborers who will be in contact with this gas if the nationwide implementation of hydrogen use is to occur.

Hydrogen's physical properties vary significantly from common fuels used today. Hydrogen is the smallest molecule, causing it to diffuse faster than today's fuels. Because of its diminutive size, hydrogen is able to leak through tiny openings 3.3 times more rapidly than air and 2.8 times quicker than methane.[13] This quality is significant when it comes to transportation and storage. Hydrogen is most commonly stored pressurized due to its low density. As a result, the pipes and containers containing the gas must be carefully fit and sealed to prevent significant leakage.

Hydrogen is extremely buoyant in air. This property coupled with hydrogen's high diffusivity rate gives the gas built in safety features for the open air environment. The hydrogen disperses up into the atmosphere so quickly in the open that it is not likely for it to accrue a large enough concentration to ignite. In contained areas with gaseous leaks the hydrogen will accumulate, initiating the need for proper ventilation systems and attentive monitoring.

Hydrogen has a broad explosive range when mixed with air in a confined area. The lowest ignition energy of hydrogen is ten times smaller than that the corresponding energies for any other gaseous fuels.[14] In addition, pressurized hydrogen burns at very high temperatures with an invisible flame that is almost impossible to detect. Currently laborers dealing with hydrogen are advised to sweep a broom with wooden bristles before them as they approach hydrogen storage facilities to aid them in detecting a hydrogen fire.[15] These attributes mark hydrogen as the most dangerous known fuel.

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[12] Basic Research Needs for the Hydrogen Economy

[13] J. Larminie and A. Dicks, *Fuel Cell Systems Explained*, Chichester, UK: John Wiley and Sons, pg. 280 (2003)

[14] Shinnar, Reuel. *The mirage of the hydrogen economy*. June 16, 2004

[15] Sage BH, Kenedy ER, Lacey WN. Phase equilibria in hydrocarbon systems. Joule-Thompson coefficient of propane. Industrial and Engineering Chemistry. 1936;28(5):601-4

The Hydrogen Infrastructure

Possible Options for Hydrogen Generation Facilities

The requirements for hydrogen delivery vary depending on the means, location, and scale of hydrogen production. Because large-scale hydrogen production methods have not been determined, the necessary infrastructure for the hydrogen economy cannot be fully developed. Although it is impossible to create specific plans for the future delivery of hydrogen from production to use, realistic solutions can be suggested. There are three general methods of hydrogen distribution that can be investigated.

Distributed production of hydrogen would occur on-site at locations such as homes, offices, and filling stations. The hydrogen could be produced on a small-scale by methods such as natural gas reformation or electrolysis of water. This method of production would require a considerable supply of energy that would most likely come from natural gas or electricity.[16] It would also call for on-site storage facilities to store hydrogen that was not currently being consumed so that the facility could supply hydrogen in peak hours of high demand. This system would not require a large-scale infrastructure to support the shipment of hydrogen from production to point of use. Barriers to this system include the safety issues that arise from allowing the public to generate their own hydrogen. Stringent training is currently required to work with hydrogen gas due to its flammable and potentially hazardous nature and having a hydrogen production facility in a garage or basement of a

Hydrogen gas could also be generated at centralized sites. These facilities would be located in areas that depended on the method of production. If the hydrogen is generated by electricity then the plant would likely be located near the site of electricity production. This site would vary depending on the type of power producing the electricity. Plants utilizing renewable sources of energy such as hydroelectric, wind, or solar power would be situated in locations dictated by nature. Centralized production of hydrogen gas would require a large infrastructure to support the "transportation, storage, and delivery of a gas or super-cooled liquid."[17] This infrastructure would require the laying of an extensive pipeline system, and would also require the creation and use of hydrogen transportation vehicles in order to reach areas where pipelines could not.

A third option would incorporate the attributes of both of the previous methods. Hydrogen producing facilities would be located in the center of areas of high population density. The facilities would have pipelines that would extend to homes and businesses in the local surrounding areas. The benefits to this option are numerous. The safety concerns associated with distributed production would be lessened because the hydrogen production could be safety monitored by trained personnel in the facilities. In addition

[16] Yacobucci, Brent D. and Curtright, Aimee E. *A Hydrogen Economy and Fuel Cells: An Overview.* CRS Report for Congress. RL32196. January 14, 2004.
[17] Yacobucci, Brent D. and Curtright, Aimee E. *A Hydrogen Economy and Fuel Cells: An Overview.* CRS Report for Congress. RL32196. January 14, 2004.

the infrastructure requirements and costs would be reduced by the ability to install pipelines that would not need to span hundreds of miles. These well-placed sites would be able to reach a large majority of the population one community at a time. However, barriers associated with the construction of hydrogen pipelines still exist, and tying these pipelines to individual homes is a complicated process.[18]

Pipelines for Hydrogen Delivery

If the development of centralized hydrogen production became necessary in the United States, then a pipeline infrastructure would be required to deliver the hydrogen from point of production to point of use. Currently 446 miles of special hydrogen pipelines operate at 100 bar in North America.[19] These pipelines are used in transporting hydrogen in oil refineries and chemical plants for industrial use. The pipelines link plants located within close proximity in order to transport collected hydrogen in recycle streams for the production of various chemicals. Hydrogen is used to eliminate sulfur from fossil fuels such as diesel and gasoline in oil refineries.[20] These pipelines are especially designed to transport hydrogen gas and are quite useful for local hydrogen delivery.

The construction of similar pipelines across the United States to deliver hydrogen to every home, office, and filling station would have astronomical costs associated with it.

If the nation is to make the switch from natural gas to hydrogen gas, then the vast natural gas delivery infrastructure would, in theory, no longer be required. Some experts have suggested the possibility of using the existing natural gas pipelines for hydrogen gas distribution to cut down on the cost of creating a new hydrogen delivery infrastructure. This idea is controversial among hydrogen experts. The main points of debate are whether or not it is physically possible to fit natural gas lines to carry hydrogen safely, and if it is possible, what the requirements would be to refit these pipelines.

The physical and chemical properties of hydrogen gas complicate the design of transportation pipelines. These properties set hydrogen apart from natural gas causing the need for major renovations of natural gas pipelines to convert them to long-range hydrogen carrying pipelines. The hydrogen molecule is the smallest possible molecule.

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[18] Yacobucci, Brent D. Personal Interview.
[19] "Hydrogen Pipelines," HyWeb, 18 Dec. 2002, Lugwig-Bölkow-Systemtechnik GmbH (LBST)/ German Hydrogen Association, www.hydrogen.org/News/arcv402e.html#LBST%20Analysis%2002-12-18, updated by B. Krue *et al.* (ref. 14), pg. 28
[20] Yacobucci, Brent D. and Curtright, Aimee E. *A Hydrogen Economy and Fuel Cells: An Overview.* CRS Report for Congress. RL32196. January 14, 2004.

Hydrogen Cars

The Demand and Concerns Regarding Filling Stations

In order for people to purchase cars fueled by hydrogen, the appropriate infrastructure must first exist. Filling stations must be both designed and built for cars to refuel. These filling stations must be large enough in number to allow for convenient refueling by hydrogen car customers. These stations must be well established before the first hydrogen car is purchased because no consumer would buy a car that could not be refueled conveniently.

To introduce hydrogen cars for commercial use on a national level, an attractive network of filling stations must exist across the country. Currently hydrogen cars exist in experimental stages and in fleets such as public transportation systems. Creating an infrastructure to support a fleet of vehicles such as a city bus system is significantly easier and less costly than one for cars because all of the vehicles in the fleet can be refueled at the same filling station and will not need to leave that local area.[21]

Associated Costs

Unfortunately the creation of filling stations is not as simple and inexpensive as adding a separate hydrogen pump at a gas station. Currently hydrogen filling stations are not even allowed to be located near gas stations due to safety reasons. They are required to be on large plots of land and must be serviced by highly skilled laborers. Servicing and constructing a filling station at the startup of the production of hydrogen cars will be extremely costly. Filling stations would require a large amount of capital for construction and would lose money for years until a significant number of people owned hydrogen cars. The associated costs and initial losses will be wholly unattractive to entrepreneurs in the private sector.

The first 10 million hydrogen car owners would be hard-pressed to find service stations to refuel. The sheer volume of filling stations required to support the introduction of hydrogen powered vehicles is overwhelming. For solely the state California, the minimum number of required filling stations is 1000. These stations are modestly expected to cost between one to two billion dollars. California contains one-eighth the population of the United States. This high population density allows California to serve more people per square mile than other areas of the country. It would be difficult to accommodate areas of lower population densities especially in the initial stages of the nationwide switch to hydrogen.

Constructing an infrastructure to support 200 million hydrogen cars is estimated to cost over one trillion dollars ($5000 per car). These estimates are based on placing the filling stations in populated areas. Current estimations foresee a small hydrogen car costing

[21] Shinnar, Reuel. *The hydrogen economy, fuel cells, and electric cars.* Technology in Society. 25 (2003) p. 455-476

somewhere between $120,000 and $150,000.[22] For a consumer to be compelled to spend so much money on a car it is of utmost importance that the vehicle be convenient to refuel.

The Hydrogen Car vs. the Electric Vehicle

Hydrogen filling stations are very different than electrical vehicle recharging stations. There are not many safety concerns involved in providing an electrical plug. Electrical outlets for electric vehicles can be located almost anywhere a car would be parked such as in garages or parking lots.

[22] Shinnar, Reuel. *The hydrogen economy, fuel cells, and electric cars.* Technology in Society. 25 (2003) p. 455-476