Hassan Khan and Youngri Kim

# Toward Meeting Tomorrow's Energy Needs: from Carbon to Hydrogen

In only two centuries since the Industrial Revolution, the human world population has nearly exhausted its stock of carbon-based fossil-energy sources. By the end of this century, complete exhaustion is likely. The race to find a replacement for carbon-based energy has scientists, politicians, and economists looking at the periodic table. Current focus shifts from the twelfth element (carbon) to the first, hydrogen.

A hydrogen-based energy economy comes with numerous grand promises: clean, easy to produce, renewable energy that can reduce greenhouse-gas emissions and the threat of global warming. While proponents of hydrogen often paint a most enticing picture, current hydrogen technology cannot yet deliver the attractive promises. The shift from a carbon-based economy to one that is hydrogen-based will requires a major effort in engineering, politics, and economic policy. Engineers attempting to make a hydrogen-based economy a reality, must confront issues at every step of the process, from safely producing hydrogen to safely storing it in our cars. Shifting to a new technology requires vast economic investments as well as the willingness of consumers to adopt that technology.

## Technological Barriers

Hydrogen is an energy carrier; unlike petroleum, where the energy is stored in the substance itself. Hydrogen needs to be produced from another energy source and then transferred in a usable form to power plants, homes and vehicles.

When a petroleum product is burned, carbon dioxide and water are produced. By contrast, burning hydrogen produces only water. Although much praised as a “clean” energy source, there are some non-clean parts to producing hydrogen fuel, depending on the production method. Many enthusiastic supporters erroneously assume that elemental hydrogen is widely available. However, much to the contrary, current methods for large-scale hydrogen production have serious environmental impacts. Steam reforming is the most widely used method for hydrogen production. This method produces hydrogen from natural gas that consists primarily of methane: $CH_4 + H_2O \rightarrow CO + 3H_2$ and $CO + H_2O \rightarrow CO_2 + H_2$.

Steam reforming emits carbon dioxide and carbon monoxide as byproducts of the process – negating the “cleanness” of hydrogen. The process is carried out by a catalytic reaction of natural gas with steam. The resulting mixture includes hydrogen, carbon monoxide, carbon dioxide, and water. Here, the mass of carbon dioxide is more than twice that of hydrogen. Although several separation processes such as liquid absorption, or pressure-swing adsorption can be used to separate hydrogen from the other components, emission of carbon monoxide and carbon dioxide into the atmosphere remains a major problem.

An old but expensive method for hydrogen production is electrolysis, decomposing water into hydrogen and oxygen by passing an electric current: $2H_2O + \text{Energy} \rightarrow 2H_2 + O_2$. Not only does this method for hydrogen production require electricity but further, it requires an extensive amount of fresh water as a feedstock. Although electrolysis has some attractive features, its requirement of electricity brings us back to the original problem of depleting current fossil-fuel resources because to make electricity, we burn fossil-fuel coal, petroleum or natural gas. At present, hydrogen from electrolysis is not used commercially.

Electrolysis of water requires 40 kWh and 2.4 gallons of water as a feedstock per kilogram of hydrogen.

Focusing on hydrogen for vehicles only, the National Research Council calculates that light-duty vehicles in the U.S. would consume101 billion kg of hydrogen per year by 2050.[1] This calculation is based on a projected path of new-car sales, new-car fuel economy, proportions of different types of vehicles, and vehicle miles traveled by the year 2050. The projected path was outlined assuming that gasoline consumption would continue to rise until the year 2015; thereafter, it would begin to decline to zero by 2050. Water requirement corresponding to 101 billion kg of hydrogen consumption annually is about 16-69 trillion gallons, assuming that electrolysis is the main hydrogen production method.[2] The water requirement to achieve the same amount, 101 billion kg of hydrogen, broadly differs based on the assumed electrolysis efficiencies.

Hydrogen production by electrolysis uses water in both direct and indirect methods. Water is used directly as a feedstock for the process and indirectly as a cooling fluid in thermoelectric generation of electricity. About 195 billion gallons per day are used today by the thermoelectric power sector to generate about 90% of the electricity in the United States.[3] However, with hydrogen production through electrolysis, water usage will increase 27-97%, depending on electrolysis efficiency and on the portion of hydrogen produced by thermoelectrically powered electrolysis as opposed to hydrogen produced from reforming of natural gas.[2] This huge water requirement is not easily met because fresh water is not plentiful. If minimizing the impact of water resources is considered a priority, and hydrogen from electrolysis becomes widespread, hydrogen production would need to be from new pathways that do not use much water (e.g. wind or solar). Further, for generating electricity, it will be necessary to develop

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1 National Research Council. The Hydrogen Economy. The National Academies Press 2004.

2 Webber, Michael E. “The Water Intensity of the Transitional Hydrogen Economy.” Environmental Research letter, 2(2007) 034007 (7pp)

3 Argonne National Laboratory, “Cost of Some Hydrogen Fuel Infrastructure Options” January 2002

new water-free cooling methods (such as air-cooling).[2]

A possible alternate method for hydrogen production has been proposed recently by researchers at Penn State University.[4] This new method uses bacteria to extract hydrogen from any biodegradable system. In a microbial electrolysis cell, the hydrogen-producing bacteria, called exoelectrogens, are used to break down acetic acid, produced by fermenting glucose, which is commonly found in ripe fruit or in the nectar of flowers, or other biodegradable organic matter. After the bacteria consume the acid, electrons are transferred from the graphite anode to the platinum cathode. In the solution, bacteria also release protons, which are hydrogen atoms stripped of electrons. As electrons are transferred to a platinum cathode, they combine with the protons and generate 0.3 volts of electricity. Adding another 0.2 volts from an outside source creates hydrogen gas.[4] This process requires much less energy than what is needed for the electrolysis of water (about 1.8V). Microbial electrolysis cells are easy to make, and the bacteria needed for the process are plentiful. This method produces up to 82 percent more energy than that stored in the required electricity and biomass because the bacteria were able to generate energy from a biodegradable system. With exoelectrogens, electricity is produced in an unconventional way. This new alternative process may provide a useful, environmentally-friendly method for small-scale hydrogen production. While the required technology for this method is still in its infancy, it provides an example of the creative innovation that we need to shift to a hydrogen-based economy.

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[4] Squatriglia, Chuck. “New Method Uses Bacteria to Generate Hydrogen Gas.” 11/02/07.

**Socioeconomic Problems**

Substituting hydrogen for gasoline will be expensive. Many critics argue that this shift will be too expensive, especially if environmental damage is to be minimized. Nevertheless, this huge cost brings several advantages. The required national building effort would create thousands of jobs and infuse billions of dollars into the economy. In the long run, a successful transition to hydrogen could end US reliance on the politically-unstable, energy- rich countries in the Middle East. From a political point of view, this advantage is perhaps, the most attractive aspect of a hydrogen economy.

The current global energy problem can be viewed as an ongoing struggle by the large energy-consuming countries of the world for energy resources that are under the control of a few states primarily in the Near East. The disproportionate power wielded by member states of OPEC (Organization of Petroleum Exporting Countries) enables disgruntled dictators to change the price of oil, sending shock waves through the global economy. Hydrogen as a fuel source could level the energy playing field, perhaps providing every country the possibility of securing its own energy resources. Therefore, the strongest backers of the hydrogen economy come from Western countries that have the financial resources necessary for pursuing the required transition.

Shifting the world's energy supply from carbon-based sources to hydrogen will require a massive economic undertaking. A successful transition requires construction of a counterpart to the existing oil infrastructure. The backbone of the infrastructure requires that a vast new production and distribution network be built for hydrogen. A 2002 study by Argonne National Laboratories calculated that the cost of building the necessary distribution infrastructure in the U.S. is approximately $500 billion.[4] Companies that deliver energy will have to retool their existing delivery system; the ubiquitous gasoline stations will have to be replaced by hydrogen-fueling stations. To convince consumers to switch to hydrogen cars, driving a hydrogen car needs to be made as easy as driving a conventional internal-combustion engine. Hydrogen fueling stations will be needed across the country; the estimated cost by Shell Oil Company is $20 billion[5]. However, this cost would only provide enough fueling stations to cover 20% of all US drivers.

**Safety Problems**

For a successful transition to a hydrogen-based economy, the safety of fuel distribution system is crucial. We need safe transfer from the hydrogen-production site to the users. Hydrogen is not easily handled due to its high diffusivity, low density as a gas and liquid and its broad flammability range relative to hydrocarbons and low-molecular-weight alcohols.[1] Another serious problem concerns safe hydrogen storage in automobiles.

Current proposals for the storage of hydrogen in automobiles range from storing liquid hydrogen at temperatures as low 20 K, to storing hydrogen dissolved in metals. Current suggestions focus mostly on the feasibility aspect of storage – i.e. will one tank of hydrogen be large enough to drive a few hundred miles? The more important problem concerns the safety threat posed by keeping a highly combustible material inside the car.

Regardless of what fuel is used, drivers will expect to be able to use their cars the way they do now: driving at high speeds for hundreds of miles between fill-ups, with safety and comfort. To maintain our driving culture, we must find a way to make sure the hydrogen inside a car remains stable in a highway-speed crash. BMW claims to have a suitable storage system for liquid hydrogen in a highly insulated tank, capable of withstanding a bullet shot directly to the tank. But this storage system has an obvious flaw due to all the extra heavy padding. New technological innovations will have to replace this brute-force method of security before

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[5] Gardner, Michael (November 22, 2004). "Is 'hydrogen highway' the answer?". San Diego Union-Tribune. Retrieved on 2008-05-09.

hydrogen cars can be considered for mass adoption.[6]

Another method of hydrogen storage is through metal hydrides. When a metal forms a stable, weak compound with hydrogen, the metal can reversibly absorb or release hydrogen gas without deterioration of the metal.[7] Although metal hydrides can provide sufficient energy by volume, energy by weight is not favorable, worse than that for gasoline. The most recently developed hydride tank for an automobile is about three times larger and five times heavier than the gasoline tank containing the same energy. Regrettably, metal hydrides react violently when exposed to moist air producing vapors that are toxic to skin or eyes. Therefore, metal hydrides have serious disadvantages.

One of the other safety issues with hydrogen follows from distribution to the public. Based on industrial use of hydrogen thus far, the safety record of professionally managed hydrogen compares favorably to that of similar industrial processes. However, safety issues are likely to arise when hydrogen is used by consumers without special training.[1]

The fueling process for consumer-owned hydrogen-powered vehicles must be monitored carefully. Due to the broad flammability range of hydrogen, a spark can cause a fire. The minimum spark energy for an ignition is low enough that a static-electricity spark created from the human body is sufficient for igniting hydrogen.[1] Thus, a safe form of grounding for the vehicle and its operator will be necessary.

Although hydrogen's high buoyancy and high diffusion rate assures that any mixture of flammable hydrogen and air disperses rapidly, in areas such as tunnels or private garages without good ventilation, detonation is a serious concern.

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[6] Pogue, David. "The Future of Hydrogen Cars" Mar 29, 2007 http://pogue.blogs.nytimes.com/2007/03/29/the-future-of-hydrogen-cars/

[7] Ergenics. "How Hydrides Work." Retrieved Jul. 5, 2007. http://www.ergenics.com/page13.htm

## Conclusion

Despite continuing advances in hydrogen-fuel technology, hydrogen for meeting our energy needs is far off because many major problems remain to be solved. Successful transition to a new technology requires advanced technology. However, a successful hydrogen economy promises numerous societal and economic benefits. The switch to hydrogen will be not only a technological change but also one with deep societal impacts. It comes with the promise of improving our lives through a healthier climate and energy independence. Although new technology may make a hydrogen economy feasible, it is not obvious that society is capable of making the switch.[8] Creating a hydrogen-based economy presents many scientific, social and political challenges.

[8] Hall, Carl T. (May 1, 2006) "Hydrogen fuel far from ready for prime time". San Francisco Chronicles. Retrieved 05-10-2008