The Barrier to Sustainable Fuel Cell Technology

By Molly Farison

April 8, 2010

I. The Potential of Hydrogen Fuel Cells

Hydrogen fuel cells are a promising technology because they provide a method by which to convert chemical energy from the abundant amount of hydrogen in the earth and its atmosphere to useful electrical energy with high efficiency. They can be used to power vehicles and generate electricity for businesses, and they have the potential to do so in a more sustainable way than gasoline and natural gas. However, natural gas is currently the main source of hydrogen used to fuel hydrogen fuel cells and gasoline is viewed as a promising possibility for hydrogen generation for fuel cell vehicles without large changes in infrastructure. The fundamental problem with fuel cell technology is that the public tends to view fuel cells as an environmentally friendly energy source, but the energy used to make that technology locally available is not all from renewable sources. Transporting hydrogen and storing it in convenient locations for users requires a large amount of energy, but producing hydrogen in usable form requires an even larger amount. Thus, finding renewable ways to generate usable hydrogen gas is the most difficult challenge in making fuel cell technology as sustainable as possible. Even if producing hydrogen from nonrenewable sources produces less carbon dioxide than burning fossil fuels, hydrogen fuel cell technology still produces greenhouse gas emissions and will not be sustainable until hydrogen is generated sustainably.

II. How Fuel Cells Work

Hydrogen fuel cells generate electrical energy from chemical energy by a process that reverses electrolysis, which is the splitting of water into hydrogen and oxygen by an electric current. Fuel cells take in hydrogen and oxygen gases, and a catalyst speeds up the formation of water by causing the hydrogen atoms to cross over to the oxygen side of the cell. Proton-exchange membrane (PEM) fuel cells are often used in fuel cell vehicles due to their relatively low operating temperatures.

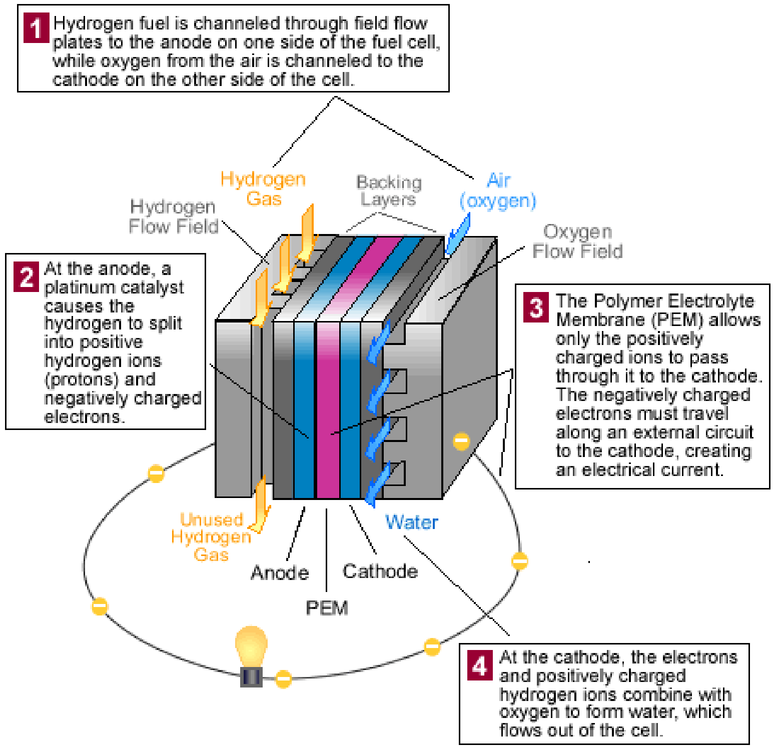

Fig. 1. *This graphic is from the U.S. Department of Energy website.[2]*

As shown in Figure 1, a semipermeable plastic membrane that lies in the middle of PEM fuel cells allows protons from hydrogen atoms to diffuse through with the help of a platinum catalyst and does not let electrons pass. In order to join with oxygen and protons to form water, the electrons must travel through a wire, through which an electric current will flow. Since each fuel cell produces only about 1.6 volts, fuel cell vehicles use large stacks of these cells. Though PEM cells are only one type of hydrogen fuel cell, all hydrogen fuel cells use the process of reverse electrolysis with a cathode, an anode, and a catalyst to generate electrical energy.

III. A Need for Hydrogen

Hydrogen, which can be used to power hydrogen fuel cells, is the most abundant element in the universe. Hydrogen is found nearly everywhere: in air, water, coal, natural gases, biomass, and outer space. Hydrogen can be extracted from all of these sources, but the amount of energy that hydrogen extraction requires presents a paradox. If the energy the hydrogen provides is not much more than the energy used to obtain it, using hydrogen as an energy carrier may not be worthwhile. Also, if the process used to obtain hydrogen emits pollutants and greenhouse gases, then running fuel cells to power vehicles and businesses is not helping to counteract global warming. Thus, renewable hydrogen generation is the greatest challenge to making fuel cell technology a sustainable source of energy because hydrogen is an energy carrier that takes energy to obtain rather than an energy source that can be harvested directly.

IV. Nonrenewable Sources of Hydrogen

A. Natural Gas

Natural gas contains a great deal of hydrogen that can be extracted through steam reforming, which involves reacting methane with steam to produce a gas composed of H_2 and CO, then converting the CO into CO_2.[3] “Steam methane reforming (SMR) generates about half of global hydrogen and more than 90 percent of U.S. hydrogen (representing some 5 percent of U.S. [natural] gas consumption).”[5] However, this gas produced by reforming needs filtration if the hydrogen is to be used for PEM fuel cells, since the cells cannot handle the CO that remains in hydrogen extracted from natural gas.[5] After years of research in SMR hydrogen generation, “the overall energy efficiency (the ratio of the energy in the hydrogen output to that in the fuel input) [has increased to] about 70 percent.”[5] SMR is currently used mostly in large hydrogen plants, but current research in small-scale versions of the technology makes it a likely candidate for hydrogen production at fuel cell vehicle filling stations.[3] “The cost of producing and delivering hydrogen from an SMR [was in 2004] projected to be $4 to $5 per kilogram, comparable to a gasoline price of $4-$5 per gallon. Depending on the fluctuating prices of gasoline, these prices could be fairly competitive. However, using natural gas to produce hydrogen makes the hydrogen fuel cell no longer a zero-emission energy source. “A fuel-cell vehicle running on hydrogen produced from natural gas would emit 25 per cent less net carbon emissions than a gasoline hybrid electric vehicle and 50 per cent less than conventional internal-combustion-engine vehicles on a well-to-wheel basis.”[4] Though these reduced emissions are an improvement on those of gasoline-burning vehicles, natural gas is not an effective long-term solution to the greenhouse gas emissions problem, which fuel cells should help solve. However, the idea of producing hydrogen at local filling stations as an alternative to transporting hydrogen directly could be crucial if hydrogen fuel cell cars are to populate the roads.

B. Gasoline

Gasoline reformers, which convert gasoline into hydrogen gas, emit less CO_2 than burning gas. Though gasoline reformers could possibly be placed on board fuel cell vehicles, the technology is currently very costly and the high operating temperature would make a car take more time to start than consumers are accustomed to.[5] In 2003, Nuvera Fuel Cells demonstrated a 75 kW gasoline reformer with over 80 percent efficiency. The start time was about a minute, but the company is continuing to decrease it.[5] Gasoline fuel cell vehicles could be an intermediate step on the way to fuel cell vehicles that contribute no greenhouse gases to the atmosphere. Their efficiency is high and gasoline is familiar to the public. As well, fuel cell cars would have over 100,000 refueling stations across the nation without any changes to infrastructure. However, unless gasoline fuel cell vehicles serve to ease the public into sustainable fuel cell vehicles, the transition from internal combustion engines to fuel cells will not do much to reduce carbon emissions.

C. Methanol

Methanol (CH_3OH) is mostly used today to produce formaldehyde, acetic acid, and the gasoline additive MTBE (methyl tertiary butyl ether).[5] As a fuel that is less flammable than gasoline, methanol has been the preferred fuel of the Indianapolis 500 for over thirty years.[5] Methanol improves performance of vehicles and biodegrades more quickly than gasoline. According to a 2001 study by the California Fuel Cell Partnership, benefits of methanol as a fuel include: " 'immediate availability without new upstream infrastructure, high hydrogen-carrying capacity, and ability to be readily stored, delivered, and carried on-board without pressurization.' "[5] Methanol reformers operate between 250°C and 350°C, which is more practical than the higher temperature for gasoline reformers.[5]

However, methanol is both toxic and corrosive, and the main source of methanol is natural gas, which when used as a source would make methanol-powered vehicles nearly useless in reducing greenhouse gas emissions. The corrosive nature of methanol would also require that pipes leading to gas stations be replaced with stainless steel, which would be costly.[5] If methanol can be produced from biomass, which contains only CO_2 that has recently been in the atmosphere, methanol could be a sustainable source of hydrogen or the sole fuel for a methanol-powered fuel cell. “Biomass resources for the production of alcohol fuels are estimated at about 5 million dry tons per day which could provide 500 million gallons of methanol per day.”[1] Methanol is a fairly common fuel that works as a substitute for diesel, so its familiarity to the public and high efficiency may allow it to dominate as a source of hydrogen, despite its emission of greenhouse gases.

D. Coal

Gasifying coal and recovering the hydrogen within it after removing impurities are processes that result in significant emissions of CO_2. Though coal is readily available, recovering hydrogen from it does not necessarily combat global warming. Producing hydrogen with electrolysis run by a 35% efficient coal plant, even with 75% efficient electrolysis and a 55% efficient fuel cell vehicle, would have a total efficiency of only 14% and burn more fossil fuel than a car running on gasoline.[6] One strategy suggested by the U.S. Department of Energy (DOE) that uses coal directly to produce hydrogen gas is this: “Use a gasification and cleaning process that combines coal, oxygen (or air), and steam under high temperature and pressure to generate a synthesis gas (syngas) made up primarily of hydrogen and CO, without impurities such as sulfur or mercury.”[5] The CO then reacts with H_2O to form H_2 and CO_2, which can be separated and sequestered. The gas that is predominantly hydrogen after most of the CO has been removed goes through pressure swing adsorption (PSA), a process that separates hydrogen from the rest of the gas mixture.[5] Sequestration of large amounts of CO_2 is currently not feasible, though this problem is a subject of research by the U.S. Department of Energy. Indeed, if sequestration of CO_2 produced by both power plants and vehicles were not an issue and could be done with low energy expended, then a transition to fuel cell vehicles and other renewable energy sources would not be as necessary to combat global warming because carbon dioxide emissions would not contribute to the greenhouse effect.

E. Nuclear Power Plants

Though simply using electricity from nuclear power plants to produce hydrogen via electrolysis is unlikely to be efficient, waste heat from power plants could be stored as energy in hydrogen. "Thermochemical water-splitting processes at temperatures exceeding 750°C could theoretically achieve 40 to 52 percent efficiency in hydrogen production [using waste heat]. Cogeneration of electricity could raise the overall efficiency to as high as 60 percent."[5] This process may not be cost-effective, but it seems that doing work with waste heat is a resourceful way to produce hydrogen for fuel.

V. Renewable Sources of Hydrogen

A. Water

Water is a renewable source of hydrogen because it is a byproduct of the reverse electrolysis that a hydrogen fuel cell performs. However, obtaining hydrogen from water by electrolysis is an energy-intensive process, and it is difficult to find a renewable source of energy that can drive the extraction of hydrogen from water. Waste heat from nuclear power plants and other plants can split water to generate hydrogen, but using waste heat is not necessarily cost-effective enough to be feasible.

B. Biomass

Since biomass (defined as anything that was once alive) contains only CO_2 that has been sequestered from the atmosphere temporarily, burning it releases no net greenhouse gases into the atmosphere. Though ethanol from corn "yields only about 25 percent more energy than was consumed to grow the corn and make the ethanol," other grasses and sources of biofuel can be produced with hardly any energy consumption.[5] Crop rotation with low-maintenance, high-energy crops would greatly increase the available biomass. DOE "believes that biofuels from nonfood crops and [municipal solid waste] could potentially cut U.S. oil imports by 15 to 20%."[1] Biomass seems to be the most viable renewable source of hydrogen in both the short term and long term, mostly because it is readily available and low cost (waste biomass more so than other types). The process of converting biomass to hydrogen is similar to coal gasification, but the CO_2 it emits can hardly be considered a contributor to global warming because the CO_2 it contains was in the atmosphere not long before. Unfortunately, production of hydrogen from biomass would have to occur in large plants rather than at refueling stations or on board a fuel cell vehicle.

C. Wind Power

Hydrogen is a way to store energy from windpower or other intermittent energy sources at night so that the energy can be used when needed. The process of converting wind energy to hydrogen need not have a high efficiency to be effective, since much of wind energy generated at night goes to waste. However, "an analysis in the May 2003 issue of *Wind Power Monthly* [argues] that in the specific case of wind power, such expensive storage [as fuel cells] may never be cost-effective or environmentally desirable" because the United States uses so little total wind power.[5] If windpower were more widespread, hydrogen storage of wind energy generated at night could make windpower an abundant source of renewable energy.

D. Photovoltaic Cells

Photovoltaic devices, which use solar energy to split water directly, use a completely renewable source of energy and hold much promise. According to a Princeton University study of the Los Angeles area, "Enough hydrogen could be produced with solar power in an area of 21 square miles to fuel one million fuel cell cars."[1] To generate hydrogen with solar energy, a semiconductor such as TiO_2 absorbs solar energy and fuctions as an electrode for electrolysis.[1] Though conversion efficiency from the energy in solar radiation to energy stored in hydrogen is less than 1%, solar energy is an abundant and renewable source of energy for generating hydrogen.[1]

E. Fuel Cells

In addition, "fuel cells themselves, especially high-temperature ones, could [generate] heat, electricity, and hydrogen [at once]. FuelCell Energy Inc. is pursuing this strategy for its molten carbonate fuel cell, as are solid oxide fuel cell (SOFC) companies."[5] Using fuel cells directly to produce hydrogen from more energy-dense fuels allows hydrogen generation to occur at refueling sites, which eliminates the problems with transporting and storing hydrogen and adds the possibility of using waste heat from fuel cells to help heat nearby buildings.

VI. Other Challenges to Sustainability

A. Transportation of Hydrogen

The flammability and low density of hydrogen also make it a difficult fuel to transport. Canisters holding hydrogen must be very well sealed due to both flammability and the high pressure needed to make hydrogen space-efficient. Pipes transporting hydrogen must be well sealed, since the gas is prone to leakage. Transporting hydrogen as a liquid is also an option, but it will remain in the liquid phase only at temperatures at or below -253°C, which is difficult to maintain even with excellent insulation.[5] Maintaining pressure for gaseous hydrogen, keeping liquid hydrogen at a -253°C, and transporting hydrogen all require energy, which much be from renewable sources in order for fuel cell technology to be sustainable.

B. Storage of Hydrogen

Handling hydrogen at fueling stations is difficult because liquid hydrogen is cold enough to cause damage to skin and gaseous hydrogen is prone to leakage.[5] A station in Munich uses robots to handle liquid hydrogen, which "requires some new techniques, like attaching the tank to the car with a magnetic holder to isolate it from thermal convection."[1] Storage of hydrogen within a fuel cell vehicle is also an issue. "A liquid hydrogen tank could be a little larger than a gasoline tank and it would offer a comparable range. A superinsulated tank can keep liquid hydrogen cold for weeks, but after a time the hydrogen would warm up and return to a gaseous state, requiring that it be vented from the tank."[1] However, if this gaseous hydrogen could be collected, it could conceivably be used to continue providing fuel to the vehicle. Since gaseous hydrogen has such a low density, pressurizing a hydrogen tank in a car to store fuel without need for a reformer contained within the vehicle is difficult for any extended range. "Direct hydrogen research has included tests with fuel tanks pressurized at 5,000 pounds per square inch, which could provide a reasonable range without a reformer."[1] Consumers have come to expect a long range for vehicles, and a range of 350 miles is close to the maximum for a storage tank that will fit in a fuel cell car. However, the 70 miles per gallon gasoline equivalent efficiency of the fuel cell vehicle helps extend the mileage per unit volume of hydrogen.

VII. Conclusion

Regardless of whether hydrogen fuel cells are economically feasible, the point of introducing hydrogen fuel cell technology is to reduce greenhouse gas emissions and move energy consumption in a more sustainable direction. While there are several fairly efficient ways to generate hydrogen with available resources, those that are sustainable are not abundant or developed enough yet to support a large fuel cell industry. Unless non-sustainable fuel cell vehicles such as those using gasoline reformers are used solely as an intermediate step to sustainability, fuel cell vehicles will not be fulfilling their intended purpose because carbon dioxide emissions will continue. While it may be necessary to go through an intermediate step in order to ease the public into a new age of energy, people must make sure to keep pursuing sustainable energy until fuel cells are worth the cost of the extensive research that is taking place. Though transporting and storing hydrogen both at refueling facilities and in vehicle storage tanks are big challenges to sustainability due to their high energy demand, finding a sustainable way to generate hydrogen that will be socially acceptable and cost-effective is a much greater challenge because hydrogen cannot simply be harvested like some other fuels.

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