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Supporting Online Material
www.sciencemag.org/cgi/content/full/305/5686/968/DC1
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VIEWPOINT

Sustainable Hydrogen Production

John A. Turner

Identifying and building a sustainable energy system are perhaps two of the most critical issues that today's society must address. Replacing our current energy carrier mix with a sustainable fuel is one of the key pieces in that system. Hydrogen as an energy carrier, primarily derived from water, can address issues of sustainability, environmental emissions, and energy security. Issues relating to hydrogen production pathways are addressed here. Future energy systems require money and energy to build. Given that the United States has a finite supply of both, hard decisions must be made about the path forward, and this path must be followed with a sustained and focused effort.

In his 2003 State of the Union Address, U.S. President Bush proposed "$1.2 billion in research funding so that America can lead the world in developing clean, hydrogen-powered automobiles." Since that time, articles both pro and con have buffeted the whole concept. The hydrogen economy (*1*) is not a new idea. In 1874, Jules Verne, recognizing the finite supply of coal and the possibilities of hydrogen derived from water electrolysis, made the comment that "water will be the coal of the future" (*2*). Rudolf Erren in the 1930s suggested using hydrogen produced from water electrolysis as a transportation fuel (*3*). His goal was to reduce automotive emissions and oil imports into England. Similarly, Francis Bacon suggested using hydrogen as an energy storage system (*4*). The vision of using energy from electricity and electrolysis to generate hydrogen from water for transportation and energy storage to reduce environmental emissions and provide energy security is compelling, but as yet remains unrealized.

If one assumes a full build-out of a hydrogen economy, the amount of hydrogen needed just for U.S. transportation needs would be about 150 million tons per year (*5*). One must question the efficacy of producing, storing, and distributing that much hydrogen. Because energy is required to extract hydrogen from either water or biomass so that it can be used as an energy carrier, if the United States chooses a hydrogen-based future it needs to think carefully about how much energy we need and where it is going to come from. In addition, sustainability must be a hallmark of any proposed future infrastructure. What energy-producing technologies can be envisioned that will last for millennia, and just how many people can they support (*6–8*)?

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Technologies for Hydrogen Production

Hydrogen can be generated from water, biomass, natural gas, or (after gasification) coal. Today, hydrogen is mainly produced from natural gas via steam methane reforming, and although this process can sustain an initial foray into the hydrogen economy, it represents only a modest reduction in vehicle emissions as compared to emissions from current hybrid vehicles, and ultimately only exchanges oil imports for natural gas imports. It is clearly not sustainable.

Coal gasification could produce considerable amounts of hydrogen and electricity merely because of the large size of available coal deposits (*9*). Additionally, because of its relatively low cost, it is often cited as the best resource for economically producing large quantities of hydrogen. However, the energy required for the necessary sequestration of CO_2 would increase the rate at which coal reserves are depleted; converting the vehicle fleet to electric vehicles and generating that electricity from "clean coal" or making hydrogen as a possible energy carrier would accelerate that depletion. Couple that to a modest economic growth rate of ~1%, and U.S. 250-year coal reserves drop to 75 years or so (*6*), which is not at all sustainable. That leaves solar-derived, wind, nuclear, and geothermal energy as major resources for sustainable hydrogen production. The hydrogen production pathways from these resources include electrolysis of water, thermal chemical cycles using heat, and biomass processing (using a variety of technologies ranging from reforming to fermentation).

Biomass processing techniques can benefit greatly from the wealth of research that has been carried out over the years on refining and converting liquid and gaseous fossil fuels. Some of these processes require considerable amounts of hydrogen, and many of these fossil-derived processes can be adapted for use with a large variety of biomass-derived feedstocks. Biomass can easily be converted into a number of liquid fuels, including methanol, ethanol, biodiesel, and pyrolysis oil, which could be transported and used to generate hydrogen on site. For the high-biomass-yield processes, such as corn to ethanol, hydrogen is required in the form of ammonia for fertilizer. Although biomass is clearly (and necessarily) sustainable, it cannot supply hydrogen in the amounts required. It remains to be seen, in a world that is both food-limited and carbon-constrained, whether the best use of biomass is for food, as a chemical feedstock, or as an energy source.

Because the direct thermal splitting of water requires temperatures of >2000°C and produces a rapidly recombining mixture of hydrogen and oxygen (*10*), a number of thermal chemical cycles have been identified that can use lower temperatures and produce hydrogen and oxygen in separate steps. The one that has received the greatest attention involves sulfuric acid (H_2SO_4) at 850°C and hydrogen iodide (HI) at 450°C (*11*). The next generation of fission reactors includes designs that can provide the necessary heat; however, a number of critical material properties must be satisfied to meet the required stability under the operating conditions of HI and H_2SO_4. For safety reasons, a fairly long heat transfer line (~1 km) is necessary, so that the hydrogen-producing chemical plant is located away from the reactor. If the issues of nuclear proliferation and reprocessing can be dealt with, then reactors based on these designs could potentially supply many hundreds of years of energy, but even that is not ultimately sustainable. Solar thermal systems could also be used to drive such thermal chemical cycles, although more interesting cycles involve the use of metal/metal oxide systems, in which solar heat is used to convert an oxide to the metal (releasing oxygen), and then the metal is reacted with water to produce hydrogen and reform the oxide (*12*).

Any technology that produces electricity can drive an electrolyzer to produce hydrogen. Because of the enormous potential of solar and wind (*13*), it seems possible that electrolysis can supply future societies with whatever hydrogen would be necessary. Figure 1 shows the cost of hydrogen from electrolysis, based on the cost of the electricity and the efficiency of the electrolyzer (note that these are system efficiencies and include all losses) (*14*, *15*). For example, some systems provide high-pressure (70-MPa) hydrogen via electrochemical pressurization. Average U.S. electricity prices range from 4.8¢ for large-scale industrial users to 8.45¢ for commercial users (*16*). Based on thermodynamic considerations alone, improvements in the efficiency of electrolysis are not going to lead to major reductions in the cost of produced hydrogen. Additionally, as the cost of electricity goes down [unsubsidized wind is already below 4¢ per kilowatt-hour (kWh)], efficiency has a lower impact on the cost of the hydrogen. Rather, improvements and innovations in the capital cost of the plant and the lifetime of the cell and its maintenance requirements are where the major cost savings will likely be obtained.

System efficiencies of commercial electrolyzers range from 60 to 73%, so one argument often used to discount electrolysis is its perceived low efficiency. However, although efficiency is certainly important, it is neither a good proxy for deciding on new technology, nor should it be the determining factor. If combined-cycle natural gas plants had the same efficiency as coal plants, they wouldn't be economical at all; and even with their higher efficiency, they produce electricity at a higher cost than coal.

The energy required to split water can be obtained from a combination of heat and electricity. At 25°C, there is enough heat in the environment that the electricity requirement drops to 1.23 V. Increasing the electrolysis temperature can lower the electrolysis voltage, but the total amount of energy required to split water remains relatively constant (actually, the isothermal potential increases slightly). Thus, higher-temperature electrolysis only makes sense if the heat is free and it only requires a small amount of energy to move it where you need it, or there is an advantage in a new material set (lower cost, longer lifetime, etc.) or a significant decrease in the electrolysis energy losses. Possible areas for heat plus electrolysis options include nuclear, geothermal, and a number of solar-based configurations.

The amount of water needed to produce hydrogen for transportation is not great. Conversion of the current U.S. light-duty fleet (some 230 million vehicles) to fuel cell vehicles would require about 100 billion gallons of water/year to supply the needed hydrogen (*17*). Domestic personal water use in the United States is about 4800 billion gallons/year. The U.S. uses about 300 billion gallons of water/year for the production of gasoline (*18*), and about 70 trillion gallons of water/year for thermoelectric power generation (*19*). Solar and wind power do not require water for their electricity generation. So not only do these resources provide sustainable carbon-free energy, they reduce the water requirements for power generation.

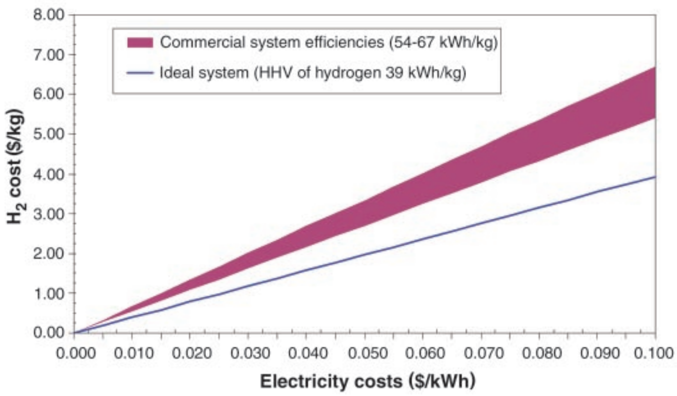

Fig. 1. The cost of hydrogen based on the electricity prices alone; no capital, operating, or maintenance costs are included in the calculation. HHV, higher heating value.

Impurities in the water can significantly reduce the lifetime of the electrolysis cell. Water is usually purified on site, but water cleanup could add to the cost of the hydrogen. In a stationary system where hydrogen is used for energy storage, the water from the fuel cell could be cycled back to the electrolyzer with minimal purification.

Sustainable hydrogen production technologies that may affect hydrogen production in the future include photobiological (*20*) and photoelectrochemical approaches (*21*–*23*). These systems produce hydrogen directly from sunlight and water, and offer the possibility of increasing the efficiency of the solar-to-hydrogen pathway (*24*) and lowering the capital cost of the system, but they still require land area to collect sunlight. These systems might allow the use of seawater directly as the feedstock instead of high-purity water.

General Comments

An important consideration is the energy payback during a time of rapid growth of a new energy or energy carrier technology. There will likely be an extended period of time when the new technologies consume more energy than they produce. The time frame for conversion to an alternative energy system is typically/historically 75 to 100 years. With this in mind, we need to think carefully about how many intermediate technology steps we introduce and how long (and at what cost) we must operate them in order to make the energy payback positive. The energy required to sustain a growth rate must also be taken into account.

Most hydrogen-producing systems being proposed are smaller than the current centralized power plants. Instead of building a small number of large generating plants, a large number of smaller plants such as wind farms and solar arrays are proposed that, when added together, can produce large amounts of energy. To be considered then is the benefit of a technology that is amenable to mass manufacturing. Much higher volumes can translate into cost savings. Electrolyzers, fuel cells, and battery technologies all fall into this area.

Although a great deal of money, thought, and energy are currently going into sequestration technologies, the question still remains: Is this the best way to spend our limited supply of energy and financial capital? As I said earlier, the best use of carbon-free sustainable electricity would be to replace coal-burning power plants (*13*). Just because we have large coal reserves does not mean that we must use them. The question is whether we have the will to leave that energy in the ground and move on to something more advanced. Sustainable energy systems can easily provide (albeit at some cost) sufficient amounts of both electricity and hydrogen. Although current gasoline-powered hybrid vehicles can reduce fossil fuel use, they cannot eliminate it. For transportation, the research, development, and demonstration of the hydrogen economy are well served by using the existing natural gas–based infrastructure. Integrating sustainable energy systems into the infrastructure would allow rapid adoption of electrolysis-based hydrogen production, whenever these future transportation systems become viable. Since the 1930s, the recognized vision of the hydrogen economy has been to allow the storage of electrical energy, reduce environmental emissions, and provide a transportation fuel. This goal is clearly achievable, but only with a sustained, focused effort.

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16. These figures are from the Energy Information Administration, available at www.eia.doe.gov/cneaf/electricity/epm/tablees1a.html.
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VIEWPOINT

Hybrid Cars Now, Fuel Cell Cars Later

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We compare the energy efficiency of hybrid and fuel cell vehicles as well as conventional internal combustion engines. Our analysis indicates that fuel cell vehicles using hydrogen from fossil fuels offer no significant energy efficiency advantage over hybrid vehicles operating in an urban drive cycle. We conclude that priority should be placed on hybrid vehicles by industry and government.

Our interest in moving toward a hydrogen economy has its basis not in love of the molecule but in the prospect of meeting energy needs at acceptable cost, with greater efficiency and less environmental damage compared to the use of conventional fuels. One goal is the replacement of today's automobile with a dramatically more energy-efficient vehicle. This will reduce carbon dioxide emissions that cause adverse climate change as well as dependence on imported oil. In 2001, the United States consumed 8.55 million barrels of motor gasoline per day (*1*), of which an estimated 63.4% is refined from imported crude oil (*2*). This consumption resulted in annual emissions of 308 million metric tons (MMT) of carbon equivalent in 2001, accounting for 16% of total U.S. carbon emissions of 1892 MMT (*3*).

Two advanced vehicle technologies that are being considered to replace the current fleet, at least partially, are hybrid vehicles and fuel cell (FC)–powered vehicles. Hybrid vehicles add a parallel direct electric drive train with motor and batteries to the conventional internal combustion engine (ICE) drive train. This hybrid drive train permits significant reduction in idling losses and regeneration of braking losses that leads to greater efficiency and improved fuel economy. Hybrid technology is available now, although it represents less than 1% of new car sales. FC vehicles also operate by direct current electric drive. They use the high efficiency of electrochemical fuel cells to produce power from hydrogen. For the foreseeable future, hydrogen will come from fossil fuels by reforming natural gas or gasoline. FC vehicle technology is not here today, and commercialization will require a large investment in research, development, and infrastructure (*4*).

Here, we evaluate the potential of these advanced passenger vehicles to improve energy efficiency. We show that a tremendous increase in energy efficiency can be realized today by shifting to hybrid ICE vehicles, quite likely more than can be realized by a shift from hybrid ICE to hybrid FC vehicles.

Energy Efficiency Model

To provide a basis for comparison of these two technologies, we use a simple model (*5*) for obtaining the energy efficiency of the various power plant– drive train–fuel combinations considered in more detailed studies (*6–11*). In general, the energy efficiency of ICEs with a hybrid drive train and from FC-powered vehicles vary depending on the vehicle configuration and the type of engine, drive train, and fuel (natural gas, gasoline, or diesel).

For each configuration, we determine well-to-wheel (WTW) energy efficiency for a vehicle of a given weight operating on a specified drive cycle. The overall WTW efficiency is divided into a well-to-tank (WTT) and tank-to-wheel (TTW) efficiency so that WTW = WTT × TTW.

We begin with the U.S. Department of Energy (DOE) specification of average passenger energy use in a federal urban drive cycle, the so-called FUDS cycle (*12*). For example, for today's ICE vehicle that uses a spark ignition engine fueled by gasoline, the TTW efficiency for propulsion and braking is 12.6% (Fig. 1A).

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Sustainable Hydrogen Production

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