Hydrogen Economy based on Renewable Energy Sources

by John A. Turner, Mark C. Williams, and Krishnan Rajeshwar

> *"Yes, my friends, I believe that water will one day be employed as fuel, that hydrogen and oxygen which constitute it, used singly or together, will furnish an inexhaustible source of heat and light, of an intensity of which coal is not capable … Water will be the coal of the future."*
>
> *— Jules Verne, The Mysterious Island (1874)*

Petroleum supplies will be in increasingly higher demand as heavily populated developing countries expand their economies and become more energy intensive. This problem is exacerbated because the U.S. alone consumes a disproportionately higher fraction (more than the next five highest consuming nations)[1] of the petroleum supply. Air quality and global climate impact are other major concerns with this continuing dependence on fossil energy sources. A recent analysis of the energy implications of future stabilization of atmospheric CO_2 content[2] concludes that researching, developing, and commercializing carbon-free primary power to the required level of 10-30 TW (10^{12} W) by 2050, could require efforts of the urgency and scale of the Manhattan Project and the Apollo Space Program.

A hydrogen-powered energy economy would be largely immune to uncertainties associated with petroleum supply from politically unstable regions of the world. The hydrogen can be produced from diverse, domestic resources using a combination of electricity generated from fossil, renewable, or nuclear sources. Hydrogen-powered fuel cells would then provide the power for both stationary and mobile (transportation) applications. Thus it is not surprising that, since the mid 1990s, there has been growing worldwide interest in a renewable hydrogen economy and fuel cell technology, as reflected in the dramatic increase in public and private sector funding in the U.S. and other parts of the world. International partnerships are also emerging to provide the infrastructure to organize, evaluate, and coordinate multinational R&D and deployment programs to speed the transition to a global hydrogen economy.[3]

This article briefly examines the salient aspects of the hydrogen economy, particularly within the context of a renewable, sustainable energy system (Fig. 1).

The Case for Hydrogen as a Fuel

Hydrogen has several important chemical properties that affect its use as a fuel

- The highest energy content per unit of weight of any known fuel—52,000 British Thermal Units (Btu) per pound (LHV) (nearly three times as much as gasoline, table I).
- An energy density per volume quite low at standard temperature and pressure. Storing hydrogen under increased pressure or at extremely low temperatures as a liquid can increase its volumetric energy density. Hydrogen can also be stored as metal hydrides.
- Highly flammable; only a small amount of energy causes ignition and burning. Its wide flammability range means hydrogen can burn when it is 4-74% of the air by volume.
- Burns with a pale blue, almost invisible flame, making hydrogen fires difficult to see. Its combustion does not produce carbon dioxide (CO_2), particulates, or sulfur emissions. Hydrogen may produce nitrous oxide (NO_X) emissions under some conditions.

Hydrogen is the simplest element and most plentiful gas in the universe. Yet hydrogen never occurs by itself in nature (at least on this planet)—it always combines with other elements such as oxygen and carbon. Once it has been separated, hydrogen is the ultimate clean energy carrier. How clean? Clean enough that the U.S. Space Shuttle program relies on hydrogen-powered fuel cells to operate shuttle electrical systems, and the crews drink one of the by-products: pure water! Hydrogen is an obvious alternative to hydrocarbon fuels, such as gasoline. It has many potential uses, is safe to manufacture, and is environmentally friendly. Today many technologies exist that can use hydrogen to power cars, trucks, electrical plants, and buildings—yet the

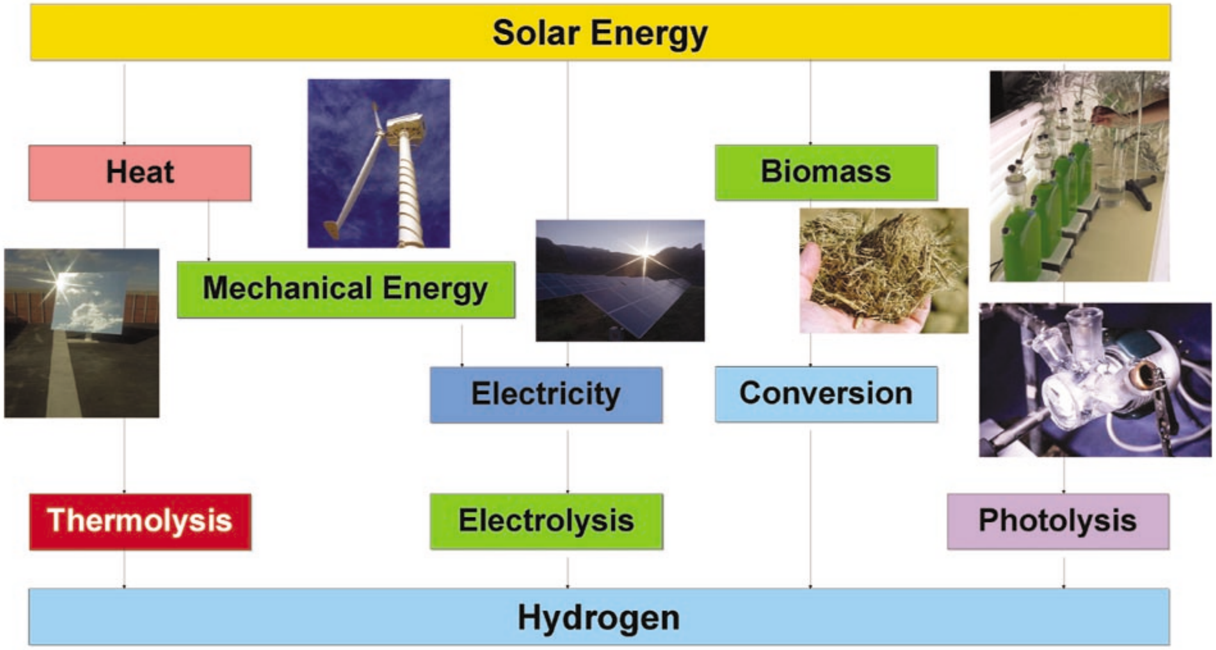

Fig. 1. Schematic diagram of the sustainable paths to hydrogen.

absence of an infrastructure for producing, transporting, and storing large quantities of hydrogen prevents its practical use.

Widespread use of hydrogen as an energy source in this country could help address concerns about energy security, global climate change, and air quality. Fuel cells are an important enabling technology for the hydrogen future and have the potential to revolutionize the way we power our nation, offering cleaner, more-efficient alternatives to the combustion of gasoline and other fossil fuels. These benefits are explained in more detail below.

Strengthen National Energy Security—Hydrogen and fuel cell technologies have the potential to strengthen our national energy security by reducing our dependence on foreign oil. The U.S. uses about 20 million barrels of oil per day, at a cost of about $2 billion a week. Much of this is used to power highway vehicles. Half the oil used to produce the gasoline you put in your automobile tank is imported. Hydrogen can be derived from various domestically available primary sources, including fossil fuels, renewables, and nuclear power. This flexibility would make us less dependent on oil from foreign countries.

Reduce Greenhouse Gas Emissions—Greenhouse gases (GHGs) are thought to contribute to global climate change. They trap excess heat from the sun's infrared radiation that would otherwise escape into space; much like a greenhouse is used to trap heat. When we drive our cars, and light, heat, and cool our homes, we generate greenhouse gases. But if we used hydrogen in very high efficiency fuel cells for our transportation and to generate power, we could significantly reduce the GHG emissions, especially if the hydrogen is produced using renewable resources, nuclear power, or clean fossil technologies.

Reduce Air Pollution—The combustion of fossil fuels by electric power plants, vehicles, and other sources is responsible for most of the smog and harmful particulates in the air. Fuel cells powered by pure hydrogen emit no harmful pollutants. Fuel cells that use a reformer to convert fuels such as natural gas, methanol, or gasoline to hydrogen do emit small amounts of air pollutants such as carbon monoxide (CO), although it is much less than the amount produced by the combustion of fossil fuels.

Improve Energy Efficiency—Fuel cells are significantly more energy efficient than combustion-based power generation technologies. A conventional combustion-based power plant typically generates electricity at efficiencies of 33-35%, while fuel cell plants can generate electricity at efficiencies of up to 60%. When fuel cells are used to generate electricity and heat (cogeneration), they can reach efficiencies of up to 85%. Internal-combustion engines in today's automobiles convert less than 30% of the energy in gasoline into power that moves the vehicle. Vehicles using electric motors powered by hydrogen fuel cells are much more energy efficient, utilizing 40-60% of the fuel's energy. Even fuel cell vehicles (FCVs) that reform hydrogen from gasoline can use about 40% of the energy in the fuel.

Table I. Energy content for 1 kg (2.2 lb) of hydrogen = 424 standard cubic feet (reacting with oxygen to form water).

Higher Heating Value	Lower Heating Value
134,200 Btu	113,400 Btu
39.3 kWh	33.2 kWh
141,600 kJ	119,600 kJ
33,800 kcal	28,560 kcal

Production of Hydrogen

The U.S. hydrogen industry currently produces 9 million tons of hydrogen per year (enough to power 20-30 million cars or 5-8 million homes). Today, hydrogen is primarily

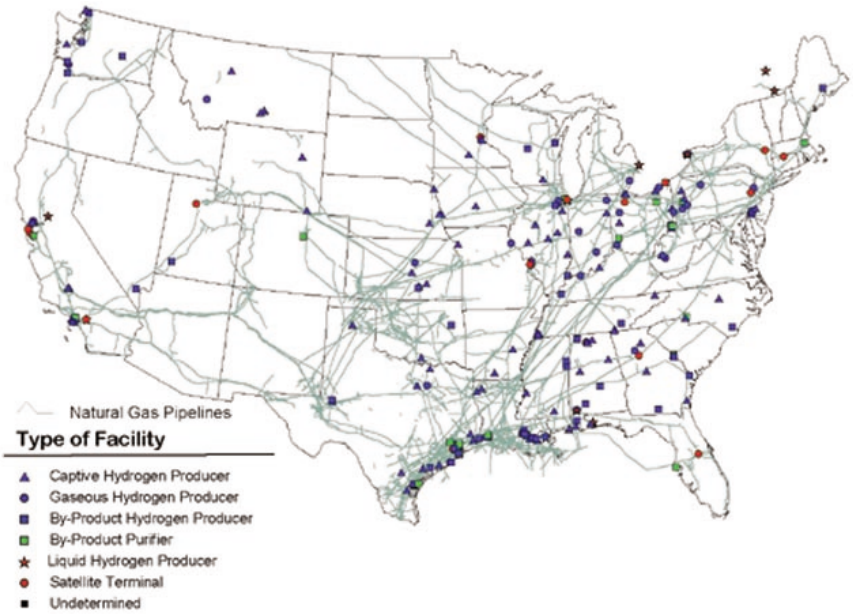

FIG. 2. Hydrogen facilities and natural gas pipeline network in the U.S.

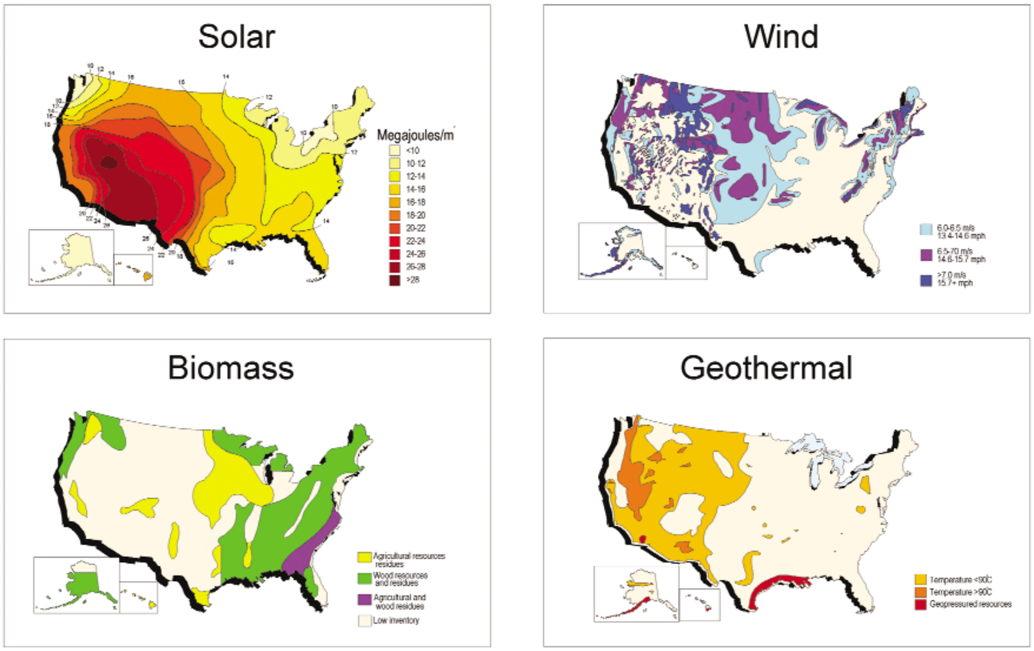

FIG. 3. Renewable energy sources in the U.S.

used as a feedstock, intermediate chemical, or specialty chemical in

- Chemicals production
- Petroleum refining
- Metals treating
- Electrical applications
- Food and soap/detergent industries

In the U.S., NASA is the primary user of hydrogen as an energy carrier. Steam methane reforming accounts for 95% of the hydrogen produced in the U.S.

Other methods of hydrogen production include

- Gasification of fossil fuels (*e.g.*, coal)
- Splitting water using electricity, heat, or light (see below)
- Thermal or biological conversion of biomass

Hydrogen is currently transported by pipeline or by road via cylinders, tube trailers, and cryogenic tankers, with a small amount shipped by rail or barge. Pipelines, which are owned by merchant hydrogen producers, are limited to a few areas in the U.S. where large hydrogen refineries and chemical plants are concentrated, such as Indiana, California, Texas, and Louisiana. Figure 2 shows how the hydrogen and natural gas pipeline is networked in the U.S. Hydrogen distribution via high-pressure cylinders and tube trailers has a range of 100-200 miles from the production facility. For longer distances of up to 1,000 miles, hydrogen is usually transported as a liquid in superinsulated, cryogenic, over-the-road tankers, railcars, or barges, and then vaporized for use at the customer site. Hydrogen can be stored as a compressed gas or liquid, or in a chemical compound (*e.g.*, hydride). The storage aspects are further elaborated in another article in this issue of *Interface*.

Renewable Energy Sources

Solar, wind, biomass, and geothermal resources constitute the major sources of renewable energy. Figure 3 shows how these resources are geographically distributed within the U.S. Any renewable energy scheme (Fig. 1) must have an integrated storage component before becoming a practically viable and sustainable system. Hydrogen is not the only storage (energy carrier) candidate in this regard. Biofuels, batteries, hydropower, flywheels, and the like all constitute approaches to match the intermittent energy supply with demand. Methanol has also been touted as an energy carrier wherein the electricity can be generated via a methanol fuel cell. However, it appears that hydrogen offers the most promise in terms of a renewable energy economy.

Consider the ramp-up in renewable energy needed to meet the projected hydrogen demand. For example, to produce 4 quads of hydrogen (*ca.* 40 million tons), enough to power 50% of the U.S. light-duty fleet based on hydrogen FCVs (at an efficiency twice the current average), would require 555 GW of wind, 740 GW of solar photovoltaic (PV), or 216 GW of nuclear power. This is based on the assumption that all the needed hydrogen is produced solely by 70% efficient electrolysis (see below) powered by the particular resource. By comparison, the current U.S. installed levels are 4.67 GW (wind), >0.1 GW (solar PV), and 98 GW (nuclear). The ramp-up challenges are clearly nontrivial and would require considerable investment. The energy payback issues are critical because these systems must produce more energy in their lifetime than is used in their manufacture and operation, or the technology is not sustainable. The energy payback for wind is only about 3-4 months which includes scrapping the turbine at the end of its life. The energy economics of solar photovoltaics (PV) are very materials-dependent. The payback for crystalline PV is about 4 years while the thin film counterparts are about 3 years; these projections include the solar cells, frames, and supports. Organic PV devices have shorter payback times relative to their inorganic counterparts but they still are in the 1-2 year range. Nuclear is about 1 year but this does not include 10,000 years of waste storage!

Water electrolysis technology is fairly well-developed.$^{4-7}$ However, using fossil-derived electricity in electrolyzers to provide hydrogen (Fig. 1) for FCVs, doubles the CO_2 emission per mile. This is clearly viable only if there is a concurrent program for major introduction of renewable generation of electricity. For the interim time frame, small scale reformers (100-1000 cars/day), generating hydrogen from natural gas would halve the CO_2 emission per mile.

Wind power appears to be promising for coupling renewable energy candidates with water electrolysis. Figure 4 charts the projected growth (installed capacity) of wind power.^{8} A 3.6 MW prototype wind turbine, with turbine blades spanning a distance equal to the wingspan of a 747 aircraft, has been installed by General Electric Co. in Spain. In the U.S., the east coast, California, and Texas all have significant installed capacity in wind power, a trend likely to see a further increase in the future (Fig. 4). Figure 5 compares the renewable energy cost trends for wind,

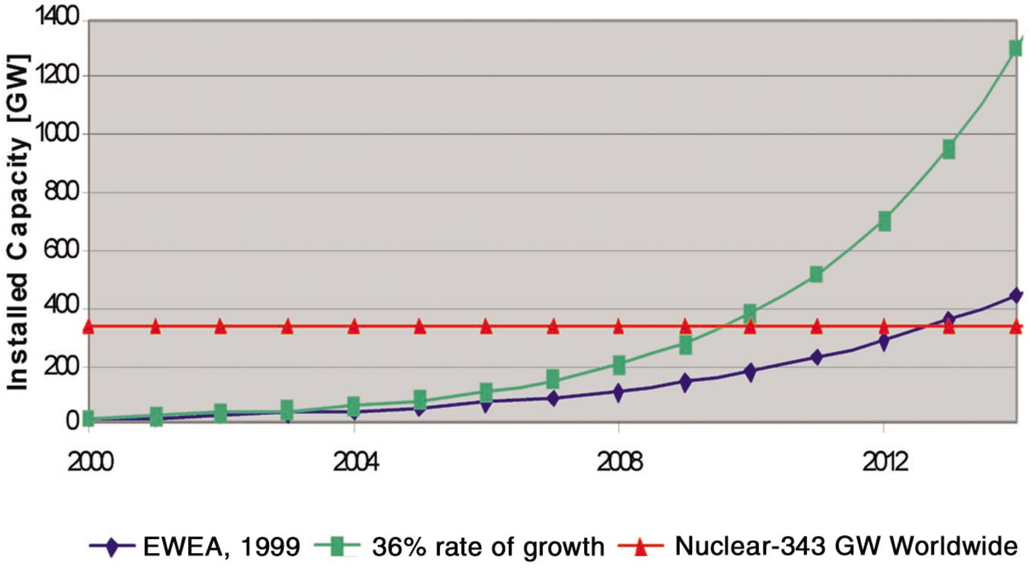

FIG. 4. *Projected growth of wind energy in the U.S. through 2014.*

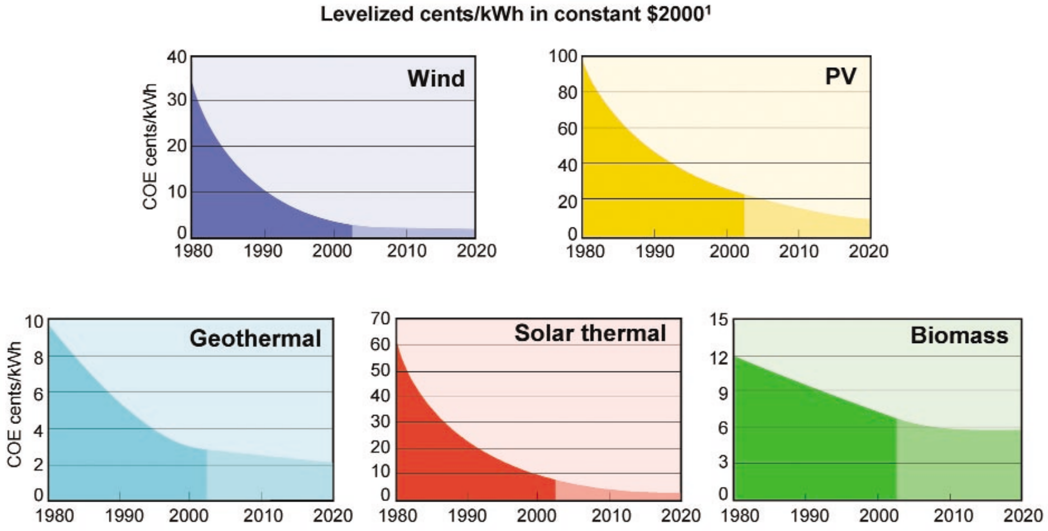

FIG. 5. *Cost trends for renewable energy in levelized cents/kilowatt-hour (constant $2000).*

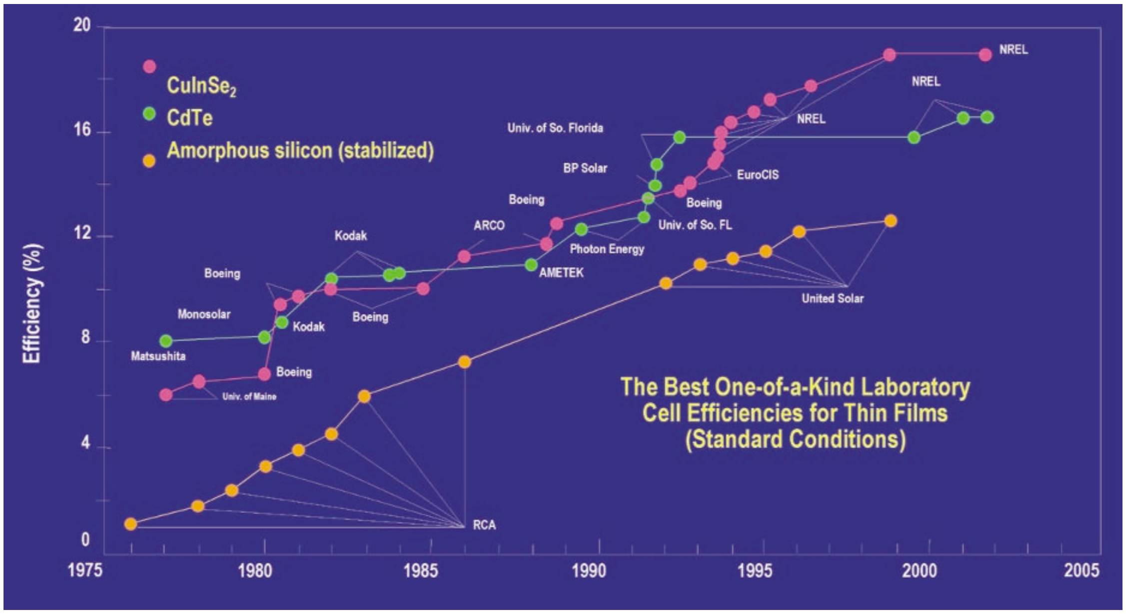

FIG. 6. Progress in the performance of thin film PV devices. The quoted efficiencies are for best one-of-a-kind laboratory solar cells.

solar PV, geothermal, solar thermal, and biomass.[9] The cost of energy (COE) parameter in each case is shown in levelized cents per kilowatt-hour at constant 2000 levels. These charts are reflections of historical cost trends rather than precise annual data.

Solar PV offers a diverse range of options for generating hydrogen; this is examined next.

Solar Production of Hydrogen

Solar energy is plentiful, especially in many parts of the U.S. (Fig. 3); is nonpolluting; can be harnessed in various ways; and is especially compatible with many developing countries, *e.g.*, India, where energy demand will soar in the future. In a solar PV device, a semiconductor-based active junction is photoexcited by sunlight to generate electron-hole pairs, which are then separated by the built-in field within the device. These photogenerated carriers can then be collected at appropriate (Ohmic) contacts to generate electric power. Solar cell efficiency levels have steadily crept up over the years for a variety of active semiconductor materials (Fig. 6).[10] The cost of the electricity produced (22¢/kWh), however, is still an order of magnitude higher than that produced from coal (2.1¢), nuclear (6.5¢), natural gas (3.6¢), oil (3.9¢), and wind (5.5¢). The potential for further cost reduction resides with the so-called third-generation solar PV devices based on concepts associated with nanostructured films, quantum dots, and organic active materials.

Harnessing the sunlight directly as hydrogen fuel in a photoelectrolysis (PE) device circumvents the need to couple a solar PV device with a water electrolyzer. The inputs in this system are sunlight and water and the outputs are hydrogen, oxygen, heat, and water. The key component of this solar PE device is the semiconductor-water active junction. Splitting water into hydrogen and oxygen (both at 1 atm) requires a thermodynamic voltage of 1.23 V at 25°C. Adding the Ohmic resistance drops and the kinetic losses translates to a net voltage of about 2 V for a practical device. The challenges then for constructing a solar PE system include optimal matching of the semiconductor absorption cross section with the solar output (taking the needed 2 eV semiconductor bandgap), finding a stable semiconductor surface under illumination in contact with water, and proper alignment of the semiconductor energy levels with the water redox positions.[11] For example, a PE system based on TiO_2 thin film[12] can absorb only a small fraction of the solar spectrum although there are efforts in many laboratories worldwide to sensitize this material to sunlight by doping and other means. Multijunction devices, including those coupling n- and p-type semiconductor-liquid junctions, are more effective in this regard. An efficient monolithic PV-PE device for water splitting has been demonstrated in the laboratory.[13]

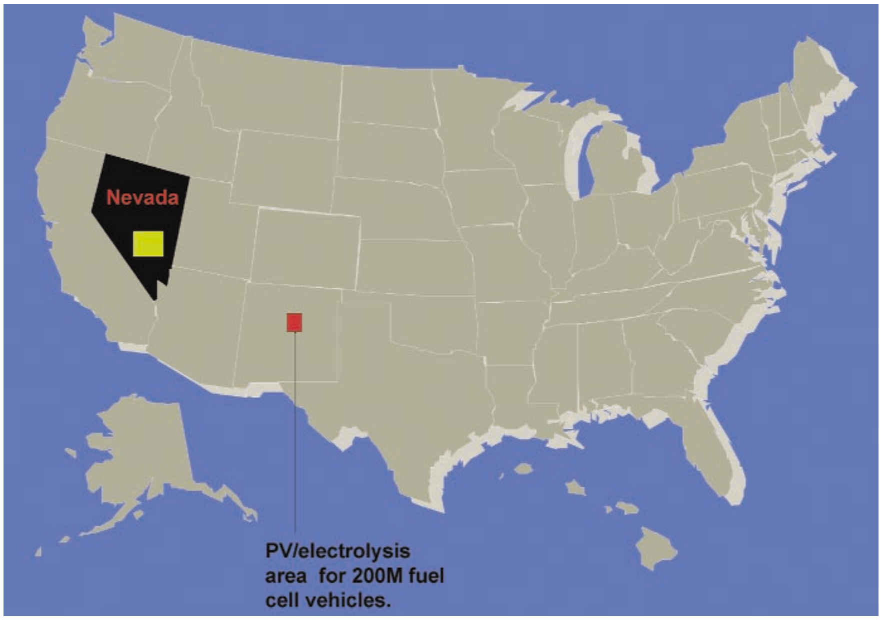

FIG. 7. Total area required for a PV power plant to meet the total U.S. annual electrical power demand (from Ref. 14).

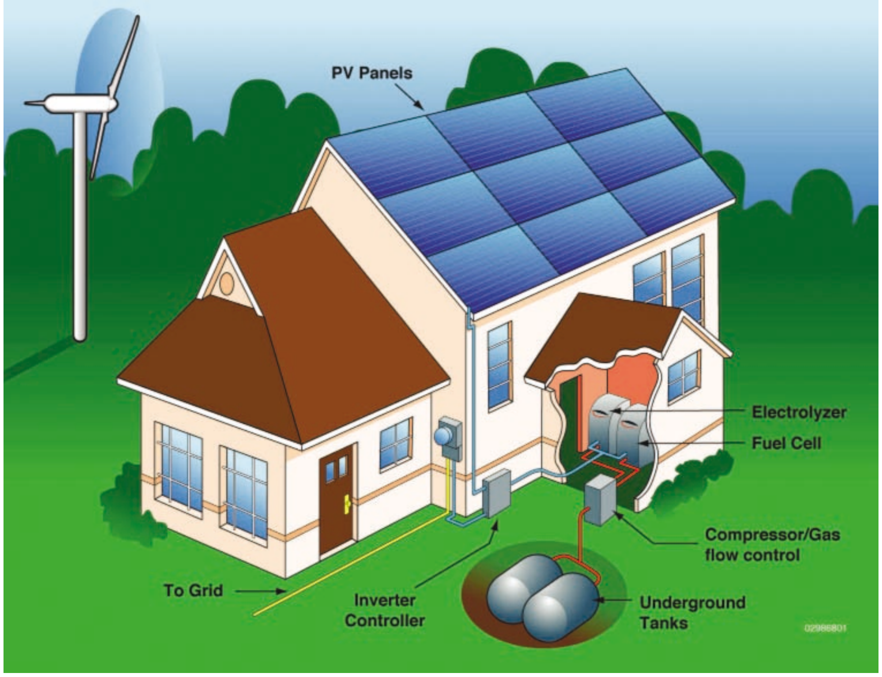

Fig. 8. Artist's rendering of a futuristic home powered by renewable hydrogen from wind and solar energy.

Other approaches to generate hydrogen from sunlight and water include photobiological approaches, homogeneous water-splitting schemes using dissolved metal complexes as catalysts, and solar thermal processes. Hybrid schemes involving a combination of a solar concentrator module (to generate the heat) and a water splitting component (to thermally evolve the hydrogen) are also undergoing R&D.

While it is true that solar energy is relatively dilute relative to fossil fuel sources, it is a fallacy that the land utilization for realistic energy demands based on solar PV technologies would be prohibitively large. Figure 7 projects the land area needed to power 200 million FCVs based on solar PE technology; a 10% device efficiency was assumed here.[14] Clearly, the required land area for solar panel coverage is not unreasonably large. Transportation obviously is not the only sector that can use renewable energy. Figure 8 contains a futuristic diagram of how a residence powered by hydrogen from wind and solar energy, may look. Fuel cells for stationary power needs are being developed by many companies in the private sector.

Water Issues and the Fuel Cell/Hydrogen Conundrum

Water is projected to be one of humanity's top ten problems for the next 50 years.[15] Demand in all sectors, domestic, agricultural, and energy, is expected to grow; in the U.S., water is already an issue for current fossil-fueled plant construction needs. In the renewable approach for generating hydrogen, water would be needed as the feedstock. While generating hydrogen from water for transportation needs would only consume a small fraction of the domestic water use (~1%) even so, it would exacerbate this problem. It is clear that water desalination plants will be necessary. For electrolysis systems, high purity water will be required and centralized water purification plants would have an advantage both in cost and in efficiency. In this case, the existing liquid fuels distribution infrastructure could be used for water delivery from coastal cities with large plants to solar hydrogen production plants. The high-purity water feedstock issue may be helped if advanced photoelectrolysis and photobiological technologies are developed to be compatible with salt water.

The produced hydrogen would be utilized in fuel cells to generate electricity. The worldwide FCV market projection for 2015 calls for 130,000-150,000 transit buses and another 17-80 million FCVs.[16,17] The corresponding hydrogen fuel demand would be 20-90 million tons per year. The current worldwide merchant capacity for this chemical is only *ca.* 2.5 million per year. The production ramp-up needed is clearly substantial and this added capital investment would not occur unless a viable fuel cell market develops. For FCVs to be acceptable to consumers, a readily accessible and reasonably priced hydrogen fuel must be available for refueling needs. Companies are not going to roll out a production and distribution system for a new fuel, unless there is a known demand. It is highly unlikely that companies are going to rely on governmental agencies for subsidies given the high (political) uncertainties associated with such a scenario (see below). The key is going to hinge on the success of current state and multicorporation initiatives to demonstrate zero-emission vehicles (ZEVs) based on fuel cells (*e.g.*, California Fuel Cell Partnership). Companies such as Dow Chemical Co. also have announced plans to team up with fuel cell manufacturers to integrate the two (disparate) technologies.

Conclusion

For hydrogen to become a viable fuel, technologies to convert hydrogen into useful energy must be further improved to increase performance and reduce cost. We have considered only fuel cells for this purpose in this article although direct combustion technologies for hydrogen also may be envisioned. There is no reason why the hydrogen infrastructure cannot evolve in a parallel fashion because most of what is developed for fossil-based hydrogen will also be applicable to hydrogen from renewable sources. Continued R&D is needed for the production of hydrogen from renewable sources so that hydrogen from non-carbon emitting sources such as solar and wind energy, will become cost-competitive. Parallel improvements in fuel cell performance and cost are needed. Government-industry partnerships such as FreedomCAR in the U.S.[3] should enable the eventual mass production of affordable FCVs and the hydrogen infrastructure to support them. Thus, the next 50 years or so will be crucial in dictating whether Jules Verne's assertions are borne out. ■

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