

HYDROGEN PRODUCTION AND STORAGE



Charles Kubert and Warren Leon

May 2011



ABOUT THIS SERIES

This briefing paper is final installment in a series of papers on fuel cells and hydrogen technologies produced by Clean Energy States Alliance (CESA). These papers are part of a larger education and outreach initiative by CESA to inform and engage state policymakers about the benefits of fuel cells, their use in critical power applications, and model state policies to support them as well as information about hydrogen production and storage:

- *Fuel Cell Technology: A Clean, Reliable Source of Stationary Power*
- *Stationary Fuel Cells and Critical Power Applications*
- *Advancing Stationary Fuel Cells through State Policies*
- *Hydrogen Production and Storage: An Overview*

For further information on CESA's hydrogen and fuel cell activities, and to download the reports, please visit www.cleanenergystates.org/projects/hydrogen-and-fuel-cells.

ACKNOWLEDGEMENTS

Many people assisted with this report, including Lewis Milford and Jessica Morey of Clean Energy Group; Maria Blais and Anne Margolis of Clean Energy States Alliance; Dr. Timothy Lipman, UC-Berkeley; Carole Read and Gregory Kleen of the US Department of Energy; and Kathy Haq of the National Fuel Cell Research Center. This four-part series was begun by Charlie Kubert (1959-2010), who completed the first three reports and laid the ground work for this final paper. Charlie was a valuable member of the CESA team, and we'd like to honor his contributions to this project. His dedication and expertise are greatly missed.

FINANCIAL SUPPORT

Support for this report was generously provided by Clean Energy States Alliance and the Department of Energy's Hydrogen Education State Partnership Project.

DISCLAIMER

Clean Energy States Alliance does not assume any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product or process that is referred to in this report. References in this report to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply endorsement, recommendation or favoring neither by the United States Government or any agency thereof, nor of the individual members of Clean Energy States Alliance. The views and opinions expressed in this series of reports do not necessarily state or reflect those of the United States Government or any agency thereof, nor the individual members of the Clean Energy States Alliance.



Introduction

When policymakers consider the expanded use of hydrogen in either vehicles or stationary applications using fuel cells, they sometimes express concern about how the hydrogen will be produced, transported, and stored. This briefing paper provides background information on hydrogen production and storage, and shows that there is already considerable experience with hydrogen. It also looks at ways to produce hydrogen from renewable resources both in the near-term and long-term. The paper's focus is on the production and storage methods needed for stationary fuel cell deployment rather than on the larger infrastructure required to support using hydrogen extensively in vehicles.

As an introduction, although hydrogen is the most common element in the universe, it cannot be mined or extracted in its elemental form. It instead needs to be separated from other compounds (such as water or hydrocarbon fuels). This conversion process requires energy, but the hydrogen produced can still be a cleaner and more reliable

source of stored energy than either fossil fuels or grid electricity.

Currently, hydrogen is widely used as a commodity chemical, with approximately 10–11 million metric tonnes produced in the US each year. If it were used directly as a fuel, that amount would be enough to power about 30 million cars or 5–8 million homes.

Hydrogen production falls into four general categories. According to the US Energy Information Administration, about 25% of the total is produced and used on-site at oil refineries, generally for “hydro-treating” crude oil as part of the oil refining process to improve the hydrogen-to-carbon ratio of the fuel. Production for ammonia for fertilizer accounts for 21%. Merchant production for sale to diverse parties for such purposes as treating metals and “hydrogenation” in food processing accounts for another 15%. Finally, about 36% of total US production is a by-product of another process, most frequently catalytic reforming at oil refineries or production of chlorine and caustic soda.



Hydrogen Production by Alkaline Electrolysis

These electrolyzers are manufactured by Hydrogen Technologies AS and each is two megawatts.

SOURCE: NORSK HYDRO



Hydrogen Production Methods

Hydrogen is produced today primarily through *steam methane reformation* (SMR), in which natural gas or another methane source is reacted with steam in the presence of a catalyst to produce hydrogen and carbon dioxide. The current cost of producing and transporting hydrogen through SMR as a dedicated process (rather than as a by-product) is \$2–\$5 per delivered kilogram.

Hydrogen can also be produced by *electrolysis*, in which water is split into hydrogen and oxygen atoms in an electrolyzer, using only electricity. This process currently costs about twice as much as SMR, although it could be more competitive in places where the cost of the electricity for electrolysis is particularly low. Electrolysis may be used as a means of storing energy. For example, the electricity produced by wind turbines during off-peak periods could produce hydrogen, which could then be stored and used to generate electricity at a later time in an on-site fuel cell system or to provide hydrogen for other applications.

Additional emerging hydrogen production methods include *gasification* or *pyrolysis* (gasification in the absence of oxygen) of coal, low-value oil refinery products or biomass, and direct solar photochemical processes. The US Department of Energy is placing particular research emphasis on hydrogen production methods that have

low overall emissions of greenhouse gases per unit of usable energy (i.e., those utilizing renewable non-carbon resources).

Hydrogen Delivery and Storage

For some stationary fuel cell applications, transportation of hydrogen is not an issue, because the hydrogen is produced on-site. That is the case with molten carbonate fuel cells, some phosphoric acid fuel cells, and solid oxide fuel cell technologies. They all directly convert natural gas or biogas into hydrogen internally within the fuel cell itself.

However, smaller stationary fuel cells, such as those using proton-exchange-membrane (PEM) technology (e.g., those used in forklifts and telecommunications towers) and some phosphoric acid fuel cells, often rely on hydrogen produced off-site and delivered in tanks to be stored on-site.

Some code officials and policymakers, as well as the general public, remain concerned about the flammable nature of hydrogen. In reality, through 40 years of industrial use, well-developed codes and standards governing hydrogen's transport, storage, and use have evolved to ensure safety. Like gasoline and natural gas, hydrogen is flammable. But also like gasoline and natural gas, it can be managed safely when the codes are followed and its properties are understood.



Compressed Hydrogen Gas Tube Trailer

This hydrogen tube trailer with 10 tubes carries 140,000 cubic feet of hydrogen at 2,800 pounds per square inch. It is made by FIBA Technologies, a manufacturer of high-pressure vessels for storing and transporting gases.



SOURCE: FIBA TECHNOLOGIES

Hydrogen Ground Storage

This ASME-certified installation of 24 tubes holds about 360,000 cubic feet of hydrogen at 2,800 pounds per square inch.

Hydrogen is often delivered in 22-foot or 44-foot steel tube trailers and can be stored on-site in the trailer vessels or transferred to code-certified pressure vessels. When needed in larger quantities or when transporting hydrogen over long distances and/or to multiple sites, it is often delivered as a liquid in a cryogenic tanker. After transport, the liquid can be transferred directly to an insulated storage vessel where it is later vaporized for use as a gas, or it can be vaporized from the tanker and used to fill on-site gaseous storage vessels. Hydrogen is also transported by pipeline, typically as a low-pressure gas. Several small hydrogen pipeline networks exist in the United States, usually near petrochemical production facilities, such as those along the Texas Gulf Coast and in Louisiana and California.

The applicable codes that states should follow are the ASME Boiler and Pressure Vessel Code, Section VIII (http://campaign.asme.org/bpvc10/Pressure_Vessels.cfm) for stationary uses and 49 Code of Federal Regulations (www.access.gpo.gov/nara/cfr/waisidx_99/49cfr172_99.html), which covers the transport of hazardous materials.

These codes specify that hydrogen cylinders and storage tanks should be stored outside at a safe distance from structures, ventilation intakes, and vehicle routes. When it is necessary to locate storage inside, the provisions in National Fire Prevention Association (NFPA) Compressed Gases and Cryogenic Fluids Code (www.nfpa.org).

[org/aboutthecodes/AboutTheCodes.asp?DocNum=55](http://www.asme.org/aboutthecodes/AboutTheCodes.asp?DocNum=55)) should be followed. Although codes and standards provide valuable guidelines, local officials have the final authority for permitting hydrogen storage and power generation facilities in a given jurisdiction.

Production of Renewable Hydrogen

Although stationary fuel cells can be highly efficient (with a combined efficiency of up to 80% when waste heat is utilized), they presently still rely primarily on non-renewable fuels such as natural gas. In the longer term, it is envisioned that cleaner and more sustainable sources of hydrogen will be employed. In fact, a number of states are facilitating this goal by offering financial incentives for fuel cell installations that employ hydrogen derived from renewable resources.

There are four key technology platforms for the production of hydrogen from renewable resources:

1. **On-site Use of Biogas:** Methane biogas is produced as a by-product of wastewater treatment, the decomposition of landfills, and anaerobic digestion of manure or food processing waste. This biogas is often used to fuel conventional reciprocating engines, but can also be used to generate power and process heat directly in an on-site fuel cell. Several wastewater treatment plants, wineries, breweries, and a food processing facility in California have installed fuel cells to utilize their



Honda's Solar Photovoltaic Hydrogen Electrolysis Station

In 2010, Honda Motor Company in Torrance, California opened a new, more compact and efficient solar-hydrogen refueling station. Solar PV panels produce electricity for hydrogen production through electrolysis. The system uses a 48-panel, 6-kilowatt solar PV system. It is designed to demonstrate what could ultimately be appropriate at the household level.

The most noteworthy feature of the prototype is the use of a new type of electrolyzer that eliminates the need for a compressor. This is expected to improve system efficiency by about 25% compared to a previous Honda prototype, while also reducing the size and cost of other key components.

The station has a modest capacity and flow rate, producing about 0.5 kg of hydrogen over 8-hours. The company projects this would be sufficient for an individual with a consistent commute to drive 10,000 miles per year. An interesting feature of the station is that it is designed to take advantage of net metering and potential future smart-grid developments by exporting electrical power to the grid during the day and then using a similar amount of energy at night during off-peak times when the cost of electricity is typically lower.



SOURCE: HONDA MOTOR COMPANY

Electrolysis Using Solar Electricity

This solar-powered hydrogen refueling station was developed by Honda to demonstrate what might ultimately be used at the household level.

on-site biogas, and California's Self-Generation Incentive Program provides enhanced incentives for fuel cells using on-site biogas. For an example, see the sidebar on Sierra Nevada Brewery.

2. **On-site Solar or Wind:** Solar panels or wind turbines installed at commercial/industrial sites to produce electricity can be used to produce hydrogen through electrolysis. AC Transit (a San Francisco Bay Area transit agency that operates a fleet of fuel cell buses) and Honda (see sidebar) are implementing demonstration projects for this.
3. **Industrial-scale Solar, Wind, Geothermal, or Hydropower:** Electrolysis-based hydrogen production facilities can also be co-located with large-scale renewable energy sites and the hydrogen then shipped to various markets. This could be a more cost-effective means of storing energy than batteries or other options. For an example, see sidebar on Hawaii.
4. **Grid Power:** Twenty-nine states currently have renewable energy portfolio standards that require utilities in the states to generate or procure an increasing share of their electricity from renewable sources. As these portfolio requirements are tightened, renewable energy will occupy an ever larger share of the country's overall energy mix. As a result, hydrogen produced from a national grid that is increasingly enriched with renewable sources, will itself become increasingly renewable-based.

It is expected that the costs of renewable energy and the processes used to convert these sources to hydrogen will decline over time. However given the current high costs for these technologies and the low cost of natural gas, steam reformation of natural gas will continue to be the low-cost source for hydrogen for the foreseeable future, whether produced on-site or off-site.

Hydrogen from Digester Gas at the Sierra Nevada Brewery

The Sierra Nevada Brewery in Chico, California produces hydrogen from by-products of brewing beer. The brewery installed four 250-kW molten carbonate fuel cells that run off a combination of natural gas and hydrogen produced from the brewery digester gas. The fuel cells provide almost 100 percent of the facility's baseload power, and the waste heat is collected as steam and used for the brewing process as well as other heating needs. The brewery is displacing 25–40% of the natural gas that it formerly used with digester gas, depending on what type of beer is being brewed.



Conclusions

Although large-scale commercialization of hydrogen vehicles will require a significant ramp-up in hydrogen production and development of an extensive delivery infrastructure, the technologies and safety standards are already in place to handle hydrogen production, distribution, and storage for stationary fuel cells and early-market material handling applications, such as forklift trucks. Most larger-scale stationary fuel cell installations produce hydrogen directly from natural gas within the fuel cell stack, eliminating the need to transport and store hydrogen. Those fuel cell applications that require on-site storage of hydrogen need relatively small amounts, which can be safely stored in approved containers.

State policymakers can confidently move forward in supporting stationary fuel cell technologies without fear of jeopardizing public safety. Even though hydrogen produced from natural gas is a relatively low-carbon carrier of energy, in the long-term, hydrogen production for both transportation and stationary power uses should move towards renewable sources of energy such as wind, solar, and biomass to produce the hydrogen. Renewable sources are already used at some production sites, for example producing hydrogen from biogas obtained from wastewater treatment. However various cost and technical

Using Hydrogen for Grid Management in Hawaii

The Hawaii Natural Energy Institute of the University of Hawaii is implementing a project to demonstrate how electrolyzers can be used to take the surplus production from renewable energy facilities and convert it to hydrogen. This approach is especially appropriate to Hawaii, which has excellent renewable resources, variability in generation from those resources, and a significant difference between base load and peak load. The electricity for the demonstration will be supplied by Puna Geothermal Venture and the hydrogen will be used by the County of Hawaii Mass Transit Agency for two shuttle buses. US DOE is Project Sponsor and the Naval Research Laboratory is Federal Technical Program Manager.

challenges remain in producing larger quantities of hydrogen at central locations from renewable sources such as solar, wind, and hydropower. State policymakers should encourage research and demonstration projects that address those challenges.

Sierra Nevada Brewing Co., Chico, CA

This 1 MW fuel cell power plant provides nearly all of the brewery's baseload power needs and the by-product steam and heat are used in the brewing process as well as other heating needs. When the fuel cell generates more power than is needed, Sierra Nevada send the excess electricity into the grid and receives net-metering credit.

SOURCE: FUELCELL ENERGY





Clean Energy States Alliance (CESA) is a national nonprofit coalition of state clean energy funds and programs working together to develop and promote clean energy technologies and markets. CESA provides information sharing, technical assistance services and a collaborative network for its members by coordinating multi-state efforts, leveraging funding for projects and research, and assisting members with program development and evaluation.

Many states across the U.S. have established public benefit funds to support the deployment and commercialization of clean energy technologies. More than twenty states are actively participating in CESA membership activities. Through these clean energy funds, states are investing hundreds of millions of public dollars each year to stimulate the technology innovation process, moving wind, solar, biomass, and hydrogen technologies out of the laboratory and toward wider use and application in business, residential, agricultural, community and industrial settings. State clean energy funds are pioneering new investment models and demonstrating leadership to create practical clean energy solutions for the 21st century.

www.cleanenergystates.org



Clean Energy States Alliance

50 State Street, Suite 1
Montpelier, VT 05602
Phone 802.223.2554
Fax 802.223.4967
Email cesa@cleanegroup.org
Web www.cleanenergystates.org

© 2011 Clean Energy States Alliance