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Renewable Hydrogen: Technology Review and Policy Recommendations for State-Level Sustainable Energy Futures

Timothy E. Lipman

Jennifer L. Edwards

Cameron Brooks

Institute of Transportation Studies ◇ University of California, Davis
One Shields Avenue ◇ Davis, California 95616
PHONE: (530) 752-6548 ◇ FAX: (530) 752-6572
WEB: http://its.ucdavis.edu/

CleanEnergyGroup
Innovation in Finance, Technology & Policy

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Timothy E. Lipman
Jennifer L. Edwards
Cameron Brooks

Prepared for Clean Energy Group

Institute of Transportation Studies
University of California—Berkeley

Hydrogen Pathways Program
University of California—Davis

Clean Energy Group

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The findings and conclusions expressed in this paper are those of the authors alone.

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Preface

We are entering a period of new opportunities for clean energy. A confluence of events in the past year has highlighted a new role for sustainable energy strategies. The ratification of the Kyoto Protocol and the emergence of regional analogues in the United States have spawned new markets and price signals for carbon dioxide and other greenhouse gas emissions reductions. Major announcements from institutional investors and the financial community have brought renewed interest in the sector. Sustained high oil prices have brought about discussion of "peak oil" and the potential inability of oil production to meet the pressures of steadily growing demand.

Over the past few years, major hurricanes such as Katrina and a series of power disruptions exposed existing vulnerabilities in our critical electricity, telecommunications, and emergency infrastructure. As energy expert Daniel Yergin opined in the *Wall Street Journal*, the 2005 storm season has underscored a "transition in the idea of energy security."

It is into this context that many are looking to hydrogen technologies as part of a sustainable energy solution. As has been the trend with clean energy innovation, state-based efforts are leading the way. California, New York, and other states have promoted bold "Hydrogen Highway" initiatives. Florida has championed hydrogen in a recently revised energy plan. A cluster of states in the Upper Midwest are collaborating on a roadmap for hydrogen technology deployment.

Still, much of the focus in these efforts has been on hydrogen applications in the transportation sector. At a relative level, precious little attention has been given to developing strategies for incorporating hydrogen into our stationary power and electricity infrastructure.

As a potential transportation fuel, hydrogen has been loudly critiqued by some experts in the energy and environment fields. Many of the criticisms have some validity in the near-term, although we would suggest that they largely ignore the overwhelming trends in energy innovation and the promising "trajectory" that hydrogen technologies have followed over the past 15 to 20 years. By most static economic analyses, hydrogen has not reached economic competitiveness in most applications.

However, looking forward several years or decades, it is clear that hydrogen remains one of the few energy storage solutions that can effectively reduce or even eliminate carbon from the energy equation—if the source for hydrogen production is properly considered and selected. Early efforts to promote fuel cell and hydrogen infrastructure development are critical to achieving these goals, recognizing that natural gas may form the foundation of this transition strategy.

Because less attention has been given in the public discourse to the potential role of hydrogen as part of a solution to stationary power, this study was commissioned to examine some of the real-world technologies and applications where there may be near-term opportunities for states to more aggressively pursue hydrogen technology solutions.

Increasingly, we are witnessing the emergence of pilot and demonstration projects that connect hydrogen and renewable energy resources. This report is intended to provide

1) a review of the current state of the commercial and technical status of hydrogen production techniques;
2) a survey of notable projects, with a focus on projects in the U.S.; and
3) policy recommendations for further exploring and advancing the potential of hydrogen as a clean fuel for stationary power and transportation applications.

We believe that these early projects represent an important opportunity to gain experience and to create linkages and learning between networks of hydrogen-related activities. There are valuable "learning-by-doing" benefits from these early projects. We conclude this report with the following specific recommendations for state action that can help develop this knowledge base and advance the prospects for renewable hydrogen production systems.

Recommendations For State Action

We have assembled several recommendations for consideration by key stakeholders who have an interest in developing strategies for promoting renewable hydrogen technologies and projects. While it is clear that there is no simple "one-size-fits-all" program for state action, they are intended to serve as a starting point for in-depth discussions that can lead to state-specific action plans and stakeholder engagement processes.

These recommendations result from our analysis of the opportunities to further explore the commercialization of these promising technologies, our assessment of previous efforts to promote clean energy and distributed power generation technologies at the state and regional levels, and our assessment of the technological status of hydrogen and renewable energy systems.

We suggest that the most cost-effective applications of public support for the introduction of hydrogen and other clean energy technologies would support their development with a comprehensive technology development/improvement and target market development effort. This type of "push-pull" strategy can help to open new markets for emerging clean energy technologies by combining support for technology R&D and manufacturing cost reductions with efforts to remove infrastructural and institutional barriers for integrating clean energy technologies into the stationary power and transportation sectors. These combined technology and market development programs have proven to be effective in the past, particularly with regard to solar PV development and deployment in Japan.

Based on analysis of the effectiveness of previous clean technology development efforts, we do not advocate programs to provide tax "holidays" and other measures to develop "industry clusters" within states and regions for fuel cell system development and manufacturing. Our research suggests that these programs are relatively expensive and have provided limited success to date where they have been tried. Unless jobs creation within a region is a primary objective, we feel that funds that might be allocated toward this type of program could be more effectively spent for other programs that could more successfully develop hydrogen and fuel cell system markets.

Hype about Hydrogen?

There are cogent and compelling concerns about the potential expansion of hydrogen from industrial uses to electrical power generation and transportation applications. These should give us pause before accepting the many claims of hydrogen proponents, especially with interest in hydrogen now reaching to the highest corporate and government offices in the country.

It is unlikely, for example, that we will witness a wide-scale hydrogen transformation for our cars, buses and trucks in the near term. Indeed, even if it were possible, it may well prove unwise, as many have challenged, given that scale requirements would tend to favor existing fossil-based energy as the hydrogen production source.

Similarly, it is likely that the highest and best use of any significant electricity production from renewable resources would be to satisfy existing demand in the electric grid in real-time, rather than for hydrogen production for powering buildings and vehicles.

Yet, while these critiques have some merit and have garnered much attention in popular discourse, they provide only snapshots of the evolving hydrogen technology landscape, ignoring significant trends that are more favorable for hydrogen. Prospective strategic planning requires looking at the trends in technology development and at societal imperatives. From this vantage, we can see a more favorable outlook for hydrogen as part of an integrated energy solution.

In these scenarios, hydrogen has a near-term value because of its fundamental characteristics of abundance, scalability, and security. Remote applications can use renewable wind and solar power to provide a local supply of hydrogen. Backup systems designed around hydrogen will be more reliable and resilient—powering telecommunications facilities in the wake of storms, to use a contemporary example. Community-based energy projects can use hydrogen as a temporary storage strategy or to capture excess energy production.

This is why the projects profiled in this report—and the resulting recommendations—are so noteworthy. They represent the vanguard of a new period of opportunities.

In most cases, these solutions will suggest a distributed model of energy production. In this sense, hydrogen and the accompanying suite of clean energy technologies will benefit from a new regulatory approach that allows for the entry of clean distributed generation (DG). Proving the potential of the technology now may provide an additional impetus to remove existing barriers and discriminatory practices.

Executive Summary

Hydrogen is emerging beyond its conventional role as an additive component for gasoline production, chemical and fertilizer manufacture, and food production to become a promising fuel for transportation and stationary power. Hydrogen offers a potentially unmatched ability to deliver a de-carbonized energy system, thereby addressing global climate change concerns, while simultaneously improving local air quality and reducing dependence on imported fossil fuels. This "trifecta" of potential benefits is sometimes missed by narrow "cost-effectiveness" analyses that examine any one of these benefits but ignore the others.

The emergence of a broader "hydrogen economy" can best be thought of as a transition that will take many years to unfold. Natural gas is a reasonable source of hydrogen in the near term, as it offers modest benefits and lower costs than most other sources. However, as the costs of hydrogen technologies such as fuel cells and electrolyzers decrease through mass production and technological learning, and costs of primary solar and wind power sources continue to slowly decrease, renewably-produced hydrogen will become more competitive.

Moreover, hydrogen costs will be relatively stable due to a diversity of feedstock base, with far more stable prices than the volatile oil and natural gas markets can offer. These reasons, coupled with the environmental benefits that hydrogen can offer if produced renewably and cleanly, have led most environmental advocates and states that are working to commercialize clean energy technologies to envision one articulated long-term scenario—a clean energy future that relies on fuel cells powered by renewably produced hydrogen.

Many states, particularly New York, Massachusetts, Connecticut, Florida, Michigan, Ohio and California, are providing research and project deployment funds, tax breaks for new industry, and other measures to encourage hydrogen and fuel cell developments in their states. These program incentives are based on the assumption that fuel cells and related hydrogen infrastructure development are likely to be important to a long-term, sustainable energy future, and that these technologies hold out hope for increased economic development in American industry. In fact, while the belief is hardly unanimous, many analysts and advocates have become convinced that fuel cells are one of the few "emission-free" technologies capable of fully transforming our energy system in a way that is urgently needed to stabilize greenhouse gas emissions and address climate change in the decades ahead.

In order to further explore the potential benefits that hydrogen can offer, we recommend a continued research and development effort, along with strategic demonstration and initial deployment efforts. Specifically, we offer the recommendations outlined in this report for consideration as a starting point for in-depth discussions that can lead to state-specific action plans and stakeholder engagement processes.

- **Dedicate Significant Funding:** State clean energy funds that currently support a broad suite of renewable energy technologies can commit significant, dedicated funding to develop action plans and programs that address the very real economic and technology barriers facing the production of hydrogen from renewable energy sources. In addition, there are significant opportunities to establish federal-state funding partnerships with agencies such as DOE, DOD and DHS that can leverage limited funding for hydrogen projects using renewable energy technologies.

- **Demonstrate the Viability of Hydrogen Storage and Production for Critical Applications:** State clean energy funds and other public interest organizations have the opportunity to support projects that can demonstrate the viability of using hydrogen storage and energy conversion in critical applications, such as telecommunications and backup power, where on-site storage of hydrogen provides important power quality and security benefits.

- **Visibly Link Hydrogen Production and Clean Energy Technologies:** Wind, photovoltaics and other projects that include clean energy technologies should be promoted as the preferred source of hydrogen production. Supporting projects that highlight the capability of producing hydrogen on-site from these sources will serve an important "ambassador" role, engendering important local and public support for hydrogen technologies. These projects can also support the acceptance of natural gas as an important transition fuel. Many states that currently support other clean energy technologies can seek opportunities to develop hybrid projects, linking together energy generation with hydrogen production and storage.

- **Establish Incentives for High-Value, On-Site Applications:** Financial incentives that target specific applications of hydrogen technology can encourage both private and public-sector players to deploy hydrogen and fuel cell technologies. High-value and niche applications for production and use of hydrogen from renewable sources (such as backup power and battery replacement) may lead to self-sustaining markets important learning-by-doing benefits and increased public acceptance.

- **Proactively Address Regulatory Incentives:** Advanced energy technologies can best be promoted with forward-thinking regulatory policies. Many states have implemented regulatory preferences and incentives (such as standby charge exemptions and net metering policies) that recognize and accommodate the public preference for and benefits from fuel cell, hydrogen and clean energy technologies. The regulatory strategies used by these early leaders can be replicated in other states. If hydrogen is to fulfill its role in a clean energy future, it will certainly be in conjunction with clean energy technologies that can operate in a distributed energy context. Currently, many regulatory barriers prevent the wide-scale adoption of clean distributed generation and limit the ability to store hydrogen on-site. These can be critical components of distributed generation projects that rely on hydrogen derived from renewable resources.

- **Accelerate Private Investment:** Successfully deploying hydrogen technologies will require significant investment from the private sector. The introduction of new technologies entails crossing what has come to be called “the valley of death”—the need for capital investments to take promising technologies from the invention and technology validation stage to the point of initial demonstration, field testing, and commercialization. These early investments can be accelerated with preferential tax treatment and other incentives to judiciously use public resources to assist and share risks with industry to develop new energy solutions. Florida, for example, has proposed significant tax benefits that could accelerate ongoing investments by Fortune 100 companies such as the recent investments by Sprint in fuel cell systems. States should consider enacting similar favorable tax policies and exemptions for projects developing hydrogen from renewable resources.

- **Develop Compelling Communications Strategies:** The potential use of hydrogen outside of the industrial sector has been hampered by public misperceptions and lack of awareness of its significant benefits. In recent years, many states have conducted sophisticated consumer and stakeholder research that has resulted in new communications campaigns to increase public understanding and support for clean energy technologies. Many states, for example, recently joined together to develop and fund a “Clean Energy: It’s Real, It’s Here, It’s Working. Let’s Make More” branding campaign. This kind of proactive communications strategy could yield tremendous results for the hydrogen sector, helping to organize currently disparate enthusiasm for hydrogen with a single, compelling message.

INTRODUCTION

Hydrogen is emerging beyond its conventional role as an additive component for gasoline production, chemical and fertilizer manufacture, and food production to become a promising fuel for transportation and stationary power. Hydrogen offers a potentially unmatched ability to deliver a de-carbonized energy system, thereby addressing global climate change concerns, while simultaneously improving local air quality and reducing dependence on imported fossil fuels. This "trifecta" of potential benefits is sometimes missed by narrow "cost-effectiveness" analyses that examine any one of these benefits but ignore the others.

Hydrogen is most efficiently used in fuel cells where it is converted to electricity "electro-chemically" (i.e. without combustion), with only water and oxygen-depleted air as exhaust products. Fuel cells hold the potential to radically shift the electric power industry to a decentralized, non-polluting system that is both more secure and more reliable. Fuel cells are currently being developed for a full range of stationary, transportation and mobile applications.

At present approximately 9 million tons of hydrogen per day are produced each year in the U.S. for the above uses and other specialized applications, such as fueling the National Aeronautics and Space Administration (NASA) space shuttles (U.S. DOE, 2006). The predominant source of this hydrogen is natural gas (which is mainly composed of methane), with crude oil being the next primary source. These fossil hydrocarbon sources of hydrogen are unsustainable in the long term, and they do not offer the environmental benefits of other, cleaner methods of production. Particularly when expanded use of hydrogen both as a transportation fuel and a source of power for buildings are being considered, we must find cleaner and more sustainable means of hydrogen production as part of a long-term sustainable energy strategy.

This can best be thought of as a transition that will take many years. Natural gas is a reasonable source of hydrogen in the near term, as it offers modest benefits and lower costs than most other sources. However, as the costs of hydrogen technologies such as fuel cells and electrolyzers decrease through mass production and technological learning, and costs of primary solar and wind power sources continue to slowly decrease, renewably-produced hydrogen will become more competitive.

Moreover, hydrogen costs will be relatively stable due to a diversity of feedstock base, with far more stable prices than the volatile oil and natural gas markets can offer. These reasons, coupled with the environmental benefits that hydrogen can offer if produced renewably and cleanly, have led most environmental advocates and states that are working to commercialize clean energy technologies envision one articulated long-term scenario—a clean energy future that relies on fuel cells powered by renewably produced hydrogen.

Many states, particularly New York, Massachusetts, Connecticut, Florida, Michigan, Ohio and California, are providing research and project deployment funds, tax breaks for new industry, and other measures to encourage hydrogen and fuel cell developments in their states. These program incentives are based on the assumption that fuel cells and related hydrogen infrastructure development are likely to be important to a long-term, sustainable energy future and that these technologies hold out hope for increased economic development in American industry. In fact, while the belief is hardly unanimous, many analysts and advocates have become convinced that fuel cells are one of the few "emission-free" technologies capable of fully transforming our energy system in a way that is urgently needed to stabilize greenhouse gas emissions and address climate change in the decades ahead. A brief review of the most notable of these efforts is included in Appendix A of this paper.

While there has been significant attention paid to the application of fuel cell technologies, the same attention has not been paid to the development of renewable hydrogen production technologies. However, many states are supporting new projects to demonstrate and develop the capacity to produce hydrogen from clean, renewable energy sources. This paper reviews many of these activities, and provides current information on the status of these hydrogen production systems and various states' efforts to promote further developments.

PURPOSE AND OBJECTIVES

The purpose of this paper is to educate state, federal, public stakeholders and other colleagues regarding:

- The current state of emerging hydrogen production technologies;
- The status of existing projects that are producing hydrogen from renewable energy sources;
- The status of major U.S. state activities for hydrogen research, development, and demonstration (included in Appendix A);
- Recommendations for new actions and incentives that could support the more successful programs; and
- A summary of complementary policy directives (and a review of existing hydrogen policy incentives) that could be used to support more renewable hydrogen projects.

We hope that this review is a useful summary of the latest developments and activities in this exciting area of technology and policy development for a more sustainable energy future.

OVERVIEW OF HYDROGEN AND FUEL CELL TECHNOLOGY STATUS

Hydrogen and fuel cell technologies are becoming commercial realities, particularly in the stationary power sector. Several companies are producing fuel cell systems for telecommunications and other power backup solutions, and stationary fuel cell systems for continuous power generation are being marketed by UTC Fuel Cells (250 kW phosphoric acid system) and Fuel Cell Energy (250 kW molten carbonate system). Fuel cells are still in pre-commercial demonstration/validation status for the transportation sector, with various fuel cell bus and passenger car demonstrations going on around the world. In the microelectronics sector, fuel cells are also pre-commercial and initially targeted for laptop computer, PDA, and cell phone applications.

The National Research Council has recently reviewed the current status of hydrogen and fuel cell technologies. Among the study's conclusions are that clean and renewable sources of hydrogen are critical and that efforts should be placed on driving down the costs of key hydrogen and fuel cell technologies. The report emphasizes the point that with future electrolyzer cost decreases, the costs of producing hydrogen from solar and wind will be dominated by electricity costs. Therefore, the study recommends that efforts should be made to drive down the fundamental renewable energy-to-electricity costs of solar, wind, and biomass power. Remaining obstacles for hydrogen introduction include capital costs and durability levels for the stationary power sector; fuel cell, reformer, and electrolyzer costs; hydrogen storage system limitations; and hydrogen infrastructure challenges for the transportation sector (NRC, 2004).

REVIEW OF HYDROGEN PRODUCTION METHODS

This section of the paper includes a brief review and summary of renewable and non-renewable hydrogen production methods and economics as well as the current status of renewable technologies and challenges to future technology development. The main hydrogen production options currently known are as follows, including a short technical and economic characterization of each production source.

Figure 1 shows that there are significant renewable energy resources distributed across the U.S. Biomass sources are fairly ubiquitous especially when municipal (landfill and wastewater treatment) sources are considered along with energy crops and crop residues. The U.S. also possesses great wind and solar potential in various regions of the country. See Appendix B for summary tables of hydrogen production cost and delivered hydrogen cost estimates.

Renewable Hydrogen Production Methods

The most common renewable hydrogen production method is the electrolysis of water using a renewable electricity source. However, significant research is being conducted into biomass-based hydrogen and other renewable methods such as photo-electrochemical water splitting and hydrogen producing algae.

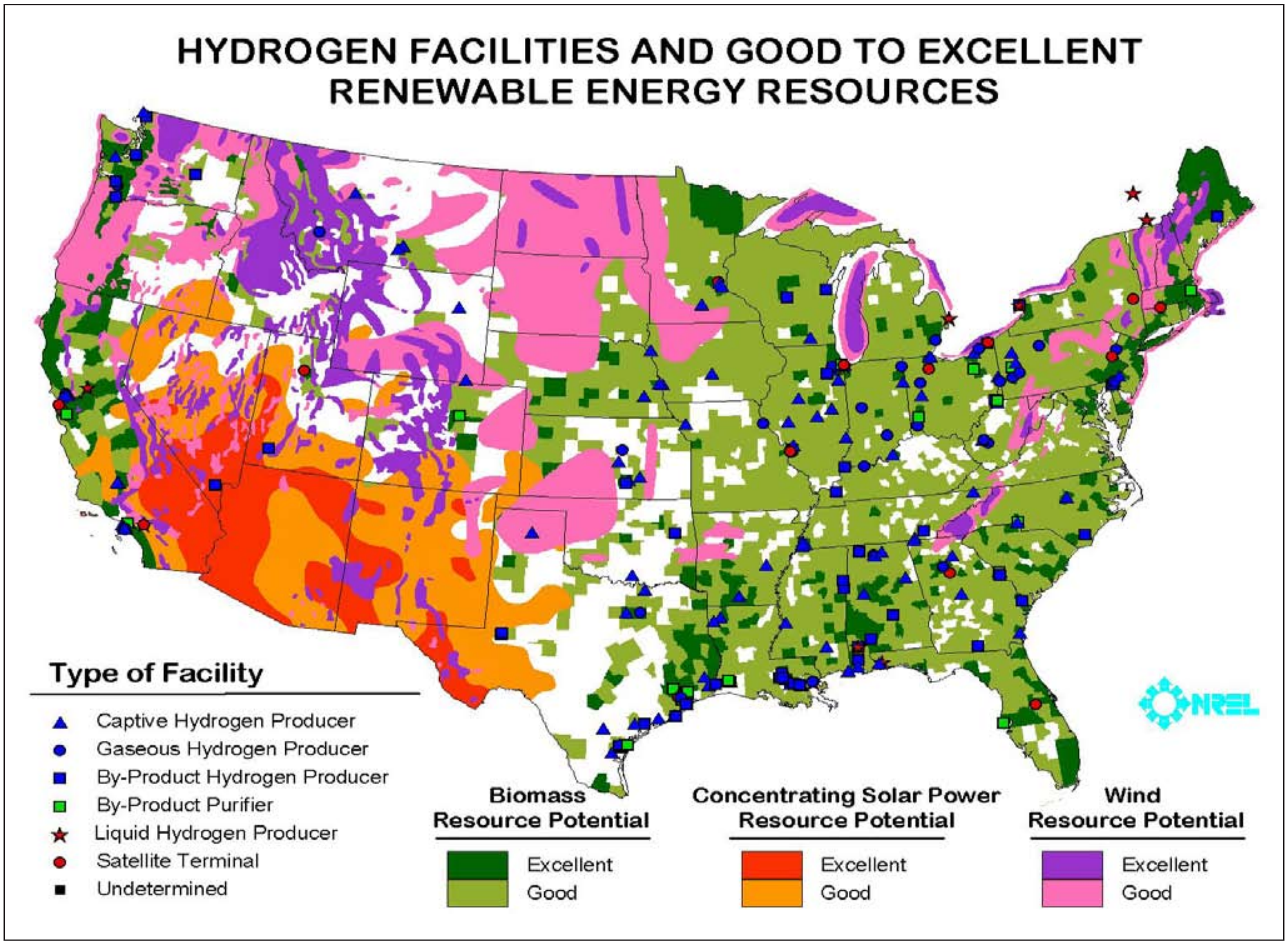
Electrolysis of Water

Hydrogen can be produced via electrolysis of water from any electrical source, including utility grid power, solar photovoltaic (PV), wind power, hydropower, nuclear power, etc. Grid power electrolysis in the U.S. would produce hydrogen at delivered costs of $6–7 per kilogram at present, with future potential of about $4 per kilogram. Wind electrolysis-derived hydrogen would cost about $7–11 per kilogram at present, with future potential of delivered costs as low as below $3 per kilogram. Solar hydrogen would be more expensive, on the order of $10–30 per kilogram at present, with future delivered costs of $3–4 per kilogram estimated to be possible. Electrolysis using PV or wind power is currently the most common method of producing renewable hydrogen.

Hydrogen from Biomass

Biomass conversion technologies can be divided into thermo-chemical and biochemical processes. Thermo-chemical processes include biomass gasification, where a biomass feedstock is heated with minimal oxygen so combustion can't take place. Gasification produces syngas, a mixture of hydrogen and carbon monoxide. Thermo-chemical processes tend to be less expensive because they can be operated at higher temperatures and therefore obtain higher

Figure 1: **Renewable Energy Potential in the U.S.**



reaction rates. They also can utilize a broad range of biomass types. In contrast, biochemical processes are limited to wet feedstock and sugar-based feedstocks. At medium production scale and liquid distribution by tanker truck, current delivered costs of hydrogen from biomass would be in the $5–7 per kilogram range. However at larger production scales and coupled with pipeline delivery, delivered costs as low as $1.50 to $3.50 per kilogram are believed possible. Pyrolysis of biomass is similar to biomass gasification. It is done completely absent the presence of oxygen and produces a liquid fuel called pyrolysis oil. Pyrolysis also offers potentially low costs of delivered hydrogen, with costs as low as about $1 per kilogram possible with large-scale production and pipeline delivery.

Other Renewable Hydrogen Production Options

Hydrogen can be produced through various other renewable methods, most of which are in early research and development stages. Direct solar thermal dissociation of water uses the high temperatures generated by solar collectors to separate water into hydrogen and oxygen. Photo-electrochemical water splitting is a form of electrolysis, but direct sunlight is used to irradiate a semiconductor immersed in water, which then produces the current necessary to split water into hydrogen and oxygen. Also, there are certain types of algae that will produce hydrogen as a byproduct of photosynthesis, requiring only sunlight, carbon dioxide, and water. Researchers in algal hydrogen production are using genetic modification techniques to increase the hydrogen conversion efficiency of algal samples. Finally, hydrogen can be produced from municipal solid waste "landfill gas" and waste gases from water treatment plants. This method of renewable hydrogen production is more established than those mentioned above, and researchers are working to demonstrate it on a commercial scale.

Non-Renewable Hydrogen Production Methods

For most near-term applications, the least expensive hydrogen production option is non-renewable, most notably steam methane reforming. However, some non-renewable methods can have highly variable feedstock costs, which is an important consideration in cost estimations. Non-renewable hydrogen production methods are listed below for comparison.

Steam Methane Reforming

Steam reformation of natural gas (or methane from other sources) produces a hydrogen rich gas that is typically on the order of 70–75% on a dry basis, along with smaller amounts of methane (2–6%), carbon monoxide (7–10%), and carbon dioxide (6–14%). Costs of hydrogen from steam methane reforming vary with feedstock cost, scale of production, and other variables and range from about $2–5 per kilogram at present (delivered and stored at high pressure). Delivered costs as low as about $1.60 per kilogram are believed to be possible in the future based on large centralized production and pipeline delivery, and delivered costs for small-scale decentralized production are projected to be on the order of $2.00–2.50 per kilogram.

Gasification of Coal and Other Hydrocarbons

In the partial oxidation (POx) process, also known more generally as "gasification," hydrogen can be produced from a range of hydrocarbon fuels, including coal, heavy residual oils, and other low-value refinery products. The hydrocarbon fuel is reacted with oxygen in a less than stoichiometric ratio, yielding a mixture of carbon monoxide and hydrogen at 1200° to 1350° C. Hydrogen can be produced from coal gasification at delivered costs of about $2.00–2.50 per kilogram at present at large scale, with delivered costs as low as about $1.50 per kilogram believed to be possible in the future.

Nuclear-Based Options

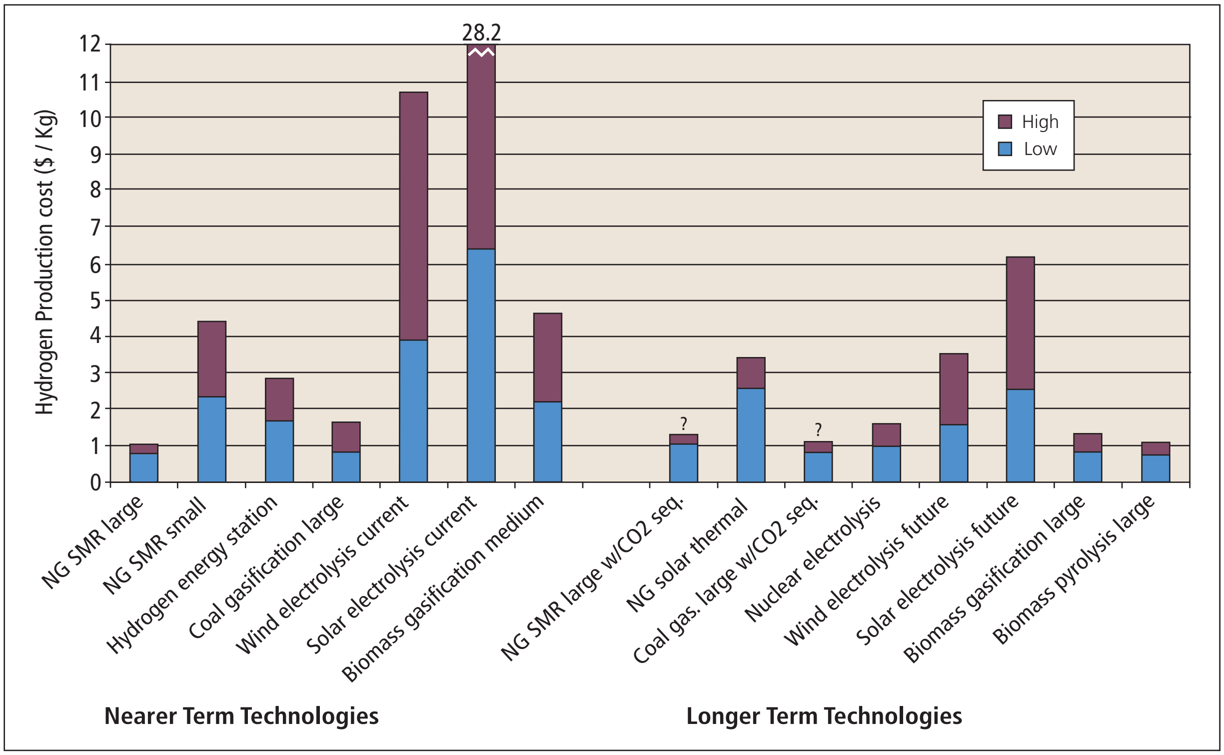
Various nuclear energy based hydrogen production schemes are possible, including nuclear thermal conversion of water using various chemical processes such as the sodium-iodine cycle, electrolysis of water using nuclear power, and high-temperature electrolysis that additionally would use nuclear system waste heat to lower the electricity required for electrolysis. Few cost studies of these schemes have yet been conducted. But at large scale and in the future, nuclear thermal conversion of water is believed to be capable of producing delivered hydrogen at costs of about $2.33 per kilogram. For the purposes of this report, nuclear options are not included as renewable.

Figures 2 and 3 present ranges in hydrogen production and delivered hydrogen costs from the technical literature. These results are directly taken from various studies and have not been adjusted for different assumptions in the studies (with regard to interest rates, feedstock costs, etc.) to make them more directly comparable.

Environmental Impacts of Hydrogen Production

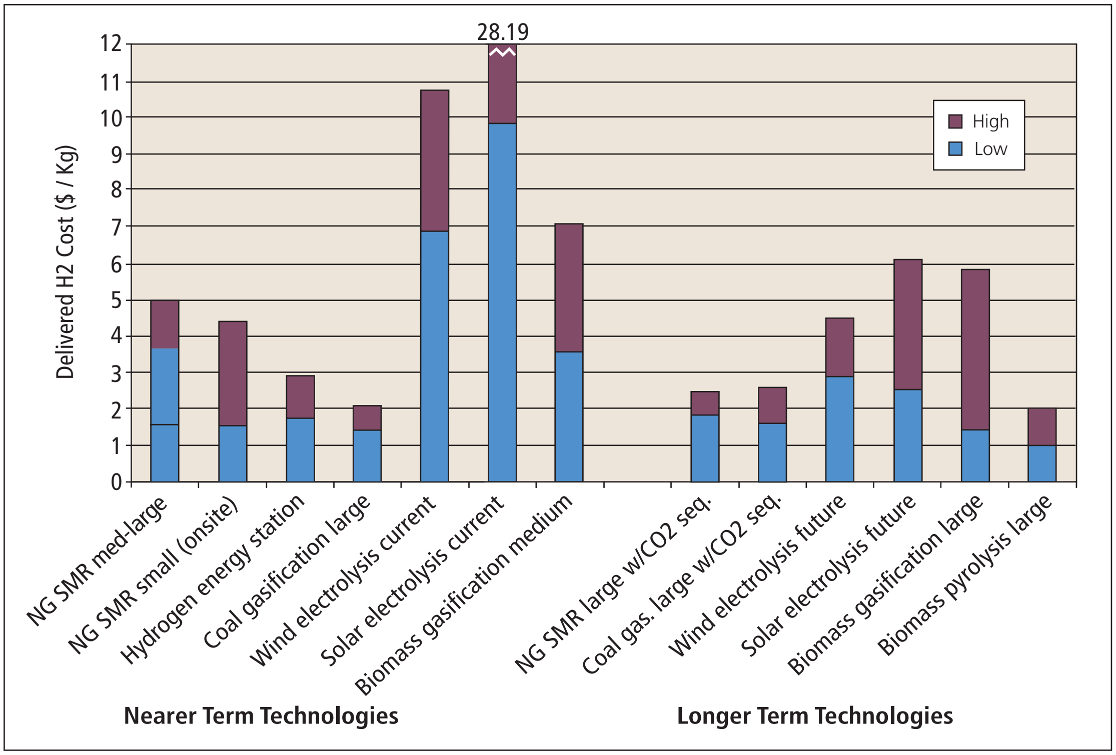
In addition to the economics of production and distribution, additional important considerations for hydrogen production methods include the environmental implications of various hydrogen production methods. These include greenhouse gas (GHG) emissions, local pollutant emissions, soil and water emissions, and land, water, and other non-feedstock resource requirements.

Figure 2: Ranges in Onsite Hydrogen Production Cost Estimates



Note: Various sources – see Table A-1 in Appendix B for details.
NG = natural gas; SMR = steam methane reforming; "?" = Costs of effective carbon sequestration from fossil fuels are uncertain because sequestration technologies and methods are still in the R&D phase.

Figure 3: Ranges in Delivered Hydrogen Cost Estimates



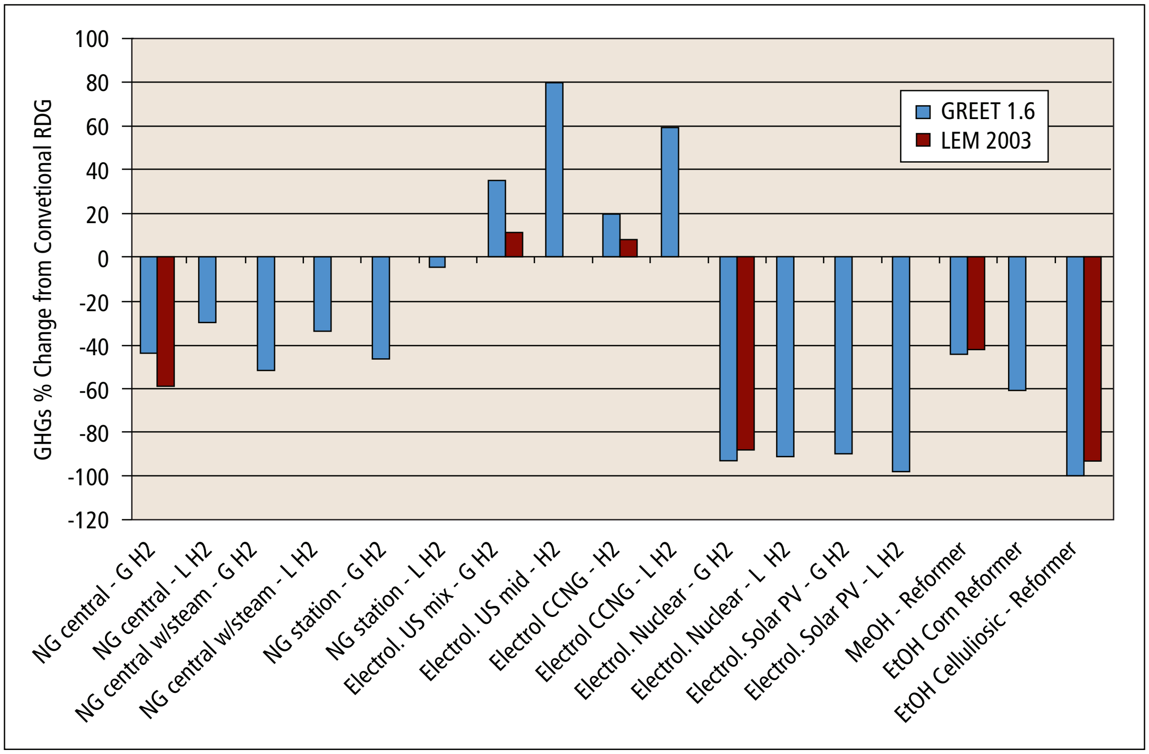
Notes: Various sources—see Table B-2 in Appendix B for details. The ranges shown are taken from many different sources, including those with assumptions that may be somewhat inconsistent with regard to production scale, interest rates, etc. Wider and narrower ranges between high and low costs thus tend to reflect the relative numbers of studies for each pathway, rather than inherent uncertainties in costs for each pathway.

In general, the GHG and air pollutant impacts of various hydrogen production pathways have been reasonably well-studied, at least for the most prominent potential production pathways, but other environmental considerations have been less well characterized. Additional studies are therefore desirable, both to more fully characterize the potential environmental impacts of hydrogen production in general and to more carefully examine the environmental impacts of hydrogen production for specific regions as these impacts will vary regionally to some extent.

Figure 4 presents estimates of full fuel-cycle GHG emissions from various hydrogen production and distribution pathways for hydrogen used in fuel cell vehicles (FCVs) relative to the GHG emissions of conventional vehicles running on reformulated gasoline. As shown in the figure, the GHG emissions associated with the production and use of hydrogen for vehicles can vary greatly depending on the production method.

In stationary settings, hydrogen used in stationary fuel cells or hydrogen combustion generator sets can typically reduce criteria pollutants and GHGs relative to central power plant generation, especially on a U.S. nationwide average basis where electricity is produced over 50% by coal-fired generation. In places like California where electricity generation is predominantly produced by natural gas, benefits can still be significant. Hydrogen used for distributed power generation allows waste heat from the power plant to be captured for local uses, known as "com-

Figure 4: **Relative Fuel-Cycle Greenhouse Gas Emissions of Hydrogen Fuel Pathways**



Notes: GREET 1.6 is the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model. LEM 2003 is the Lifecycle Emission Model. CCNG = combined cycle natural gas power plant; EtOH = ethanol; G = gaseous; L = liquid; NG = natural gas; MeOH = methanol; PV = photovoltaics; RFG = reformulated gasoline.

bined heat and power" or "cogeneration." This waste heat re-capture allows for overall thermal efficiencies of up to 90% (combined with electrical efficiencies of 45–60%), without transmission losses, vastly improving on the efficiency of centralized electricity generation.

RECENT RESEARCH ON HYDROGEN PRODUCTION METHODS

The following section of this paper reviews recent research activity for renewable hydrogen production in the U.S. This section discusses some of the new and pioneering methods of renewable hydrogen production—those that are still in research and development stages. These efforts are largely conducted by national laboratories and universities, but also by other research organizations and the private sector.

Hydrogen Production from Biomass

Pyrolysis is a thermo-chemical process that produces oil from solid biomass feedstocks and holds promise as a new renewable hydrogen production method when the pyrolysis oil is reformed. Researchers at the National Renewable Energy Laboratory (NREL) are studying catalytic reforming of biomass pyrolysis products, primarily to find regenerative, fluidizable catalysts with waste stream flexibility. Notable research on hydrogen production from biomass also includes expanding the options for biomass feedstocks, especially post-consumer waste products. NREL researchers are examining hydrogen production from post-consumer residues, including plastics, trap-grease (recovered from sewer lines), and synthetic polymers. Plastics require first a fast-pyrolysis stage and then a steam reforming stage, while trap-grease requires only steam reforming. Researchers at Iowa State University are working to produce hydrogen through biomass gasification of agricultural products, specifically switchgrass and corn stover.

At Penn State University, a research team led by Bruce Logan at the Hydrogen Energy Center has several projects on biomass-based hydrogen that use bacteria and microbial fuel cells to produce hydrogen from wastewater. Microbial fuel cells can be used to produce either electricity or hydrogen and are still in early laboratory stages of development. The National Science Foundation is funding a project to develop methods of hydrogen production from wastewater with a high carbohydrate content will extract the hydrogen from fermentation byproducts. US Filter is funding a project to demonstrate hydrogen production at an industrial wastewater treatment site. The Hydrogen Energy Center is also working on genetic engineering of hydrogen-producing bacteria to increase the efficiency of hydrogen production through fermentation.

Algal Hydrogen Production

Researchers at the University of California at Berkeley, in collaboration with Oak Ridge National Laboratory, are leading research on hydrogen production from algae. The goal is to increase the conversion efficiency of sunlight to hydrogen in the green algae species Chlamydomonas reinhardtii by using genetic modification techniques. Researchers have determined that a large chlorophyll antenna size reduces hydrogen production in the algae species. Screening and genetic alteration techniques are being used to reduce the antenna size of organism samples. The light utilization efficiency of naturally-occurring algae is 3–5%, and a theoretical maximum efficiency is 30%. Research goals are to hit a 15% utilization efficiency by 2010. Researchers at NREL are also working on improving methods of biological water splitting by screening for organisms that have a high oxygen tolerance. Key research goals include engineering biological organisms that will produce hydrogen in an oxygen-rich environment, with a 2010 target of continuous hydrogen production up to 1,500 hours.

In related research, Sandia National Laboratory is developing nanotubes to split water into hydrogen and oxygen using direct sunlight. The Sandia nanotubes are composed entirely of porphyrins, molecules related to chlorophyll. The porphyrin nanotubes are combined with platinum and gold catalysts to produce a water-splitting device. These systems have been developed and tested on a laboratory scale, and Sandia researchers are working on reducing the scale of the devices.

Photo-Electrochemical Water Splitting

Photo-electrochemical water splitting is based on the same chemical principles as the technique of electrolysis. Semiconductors are immersed in an electrolyte and irradiated with sunlight, thereby releasing a current that splits water molecules. Several research institutions are working to increase the efficiency of photo-electrochemical water splitting. At Virginia Polytechnic University, Karen Brewer's laboratory focuses on the electrochemical properties of devices used in photo-electrochemical water splitting. The lab designs "supramolecular" complexes to increase the efficiency of solar hydrogen production. Two electrons are required to separate the hydrogen and oxygen of a water molecule; this research exploits the special properties of rhodium to collect excited electrons in pairs to efficiently react with water molecules. NREL researchers are also studying photo-electrochemical water splitting, with research goals of a solar-to-hydrogen efficiency of 10% and a target hydrogen cost of $3/kg.

Finally, notable breakthroughs for renewable hydrogen production have occurred at Purdue University where Mahdi Abu-Omar's research group studies hydrogen production by adding a metal catalyst to a mixture of water and an organic liquid called organosilane. When the catalyst is added, the oxygen molecule from water bonds with a silicon molecule from the organosilane. The hydrogen can be produced in ambient conditions. Costs of the process have not been estimated, though the cost of organosilanes may be the prohibiting factor. One possibility for cost reduction is to recycle the silicon byproduct. The process has not been tested on a large scale.

For more information on the above research activities:

National Renewable Energy Laboratory Renewable Hydrogen Website
http://www.nrel.gov/hydrogen/proj_production_delivery.html

Iowa State University, Robert Brown Faculty Page
http://www.cbe.iastate.edu/brown/

Penn State University Hydrogen Energy Center
http://www.engr.psu.edu/h2e/

Sandia National Laboratory Press Release
http://www.sandia.gov/news-center/news-releases/2005/renew-energy-batt/nano.html

Virginia Polytechnic University, The Brewer Group
http://www.chem.vt.edu/chem-dept/brewer/energyresearch.htm

Purdue University, Mahdi Abu-Omar Faculty Page
http://www.chem.purdue.edu/people/faculty/faculty.asp?itemID=3

REVIEW OF RECENT HYDROGEN DEMONSTRATION PROJECTS

The next section of this paper reviews recent or planned demonstration projects of renewable hydrogen systems in the U.S. and internationally. Information was collected from personal interviews, industry reports and newsletters, progress reports available for publicly funded projects (primarily through the DOE's Hydrogen, Fuel Cells and Infrastructure program), and newspaper and journal articles. The projects that were reviewed for this report do not represent a comprehensive list of renewable hydrogen activity, but they are a subset of notable projects for which information was publicly available.

Brief summaries for each of the 25 projects reviewed for this report are given in Box 1. In addition, four U.S. projects are described in more detail in the following section. These projects illustrate the opportunities for states to pursue similar demonstrations projects. Most of these demonstration projects reviewed here are fully operational, but some notable projects have been included if project funding has been secured, even if the project has not been completed.

Of the projects reviewed, 11 are in the U.S. and 14 are international. The majority of renewable hydrogen demonstration projects are electrolysis-based (19 total), dominated by wind electricity; some PV examples are available as well. Two projects produce hydrogen from biomass (both in the U.S.), and 3 projects use different methods of solar hydrogen production: a demonstration using solar collectors to heat zinc oxide in Israel, a solar and landfill gas demonstration in Canada, and a photo-electrochemical "tandem cell" demonstration in the U.K. Additionally, a renewable hydrogen demonstration is planned for the 2008 Beijing Olympic Games, but the method of hydrogen production has not been determined.

More than half of the U.S. based projects received some federal, state, or local agency funding, and 2 projects received funds from both federal and state sources. A significant source of federal funding is through the DOE's Hydrogen, Fuel Cells, and Infrastructure program, but one project also received funds from the Department of Defense's Climate Change Fuel Cell Program and another directly through the federal appropriations process. State and local funds came from a variety of different offices and programs, some energy-specific and some for environmental projects, though no programs were specifically targeting renewable hydrogen. Of the 11 U.S. projects, one was privately funded at an eco-retreat in New Mexico.

Table 1: U.S. and International Renewable Hydrogen Demonstration Projects

U.S. PROJECTS
Hydrogen Production from Renewables-Based Electrolysis
1. Hydrogen Fueling Station at the Burlington, Vermont Department of Public Works This is a grid-connected PEM electrolyzer that will generate hydrogen for converted vehicles at the Burlington Department of Public Works. The Burlington Electric Department generates a large portion of its electricity from renewables and will donate credits from a windmill that is adjacent to the site of the fueling station. More information on this project is available in the featured projects section below. *http://www.northernpower.com/news/press-releases.html?news_id=16978&year=2005&month=11&superstep=12* *http://www.distributed-energy.com/press/corporate.html?news_id=16997&year=2005&month=03*
2. Residential Solar to Hydrogen System in New Jersey This is a residential home in East Amwell, New Jersey that will use a PV system for primary electricity, and excess output will be used to generate hydrogen via electrolysis. The hydrogen will be used in a fuel cell for off-peak electricity production for the home. In addition, there are plans to use the waste heat from the fuel cell to supplement a geothermal heat pump. More information on this project is available in the featured projects section below. This project is being supported by the New Jersey Board of Public Utilities, a member of the Clean Energy States Alliance and Public Fuel Cell Alliance.
3. Wind-to-Hydrogen Demonstration in Minnesota This is a research project at the University of Minnesota's Morris campus. A 1.65 MW wind turbine was erected in 2005 to supply electricity to the campus. The next phase is to integrate a 400 kW electrolyzer for hydrogen production. The hydrogen will be used for research and demonstration projects, including storage of intermittent wind power using hydrogen, mixing hydrogen with natural gas as a fuel, and using renewable hydrogen for fertilizer production. More information on this project is available in the featured projects section below. *http://www1.umn.edu/iree/funded_projects.html*
4. Schatz Solar Hydrogen Project This system is located at Humboldt State University's Telonicher Marine Laboratory in Trinidad, California. The PV-fuel cell system runs the compressor on the aerator for the site's aquarium. The system consists of a 7 kW PV array, a 6 kW electrolyzer capable of producing 20 standard liters of hydrogen per minute, and a 1.5 kW PEM fuel cell. The system has been operational since 1991. *http://www.humboldt.edu/~serc/trinidad.html*
5. PV-Based Electrolysis Station at Florida Wildlife Park Progress Energy Florida is constructing a renewable hydrogen and fuel cell system for the Florida Department of Environmental Protection at its Homosassa Springs State Wildlife Park. The system will use a 5 kW PV panel for hydrogen production and will provide a portion of the electricity needs at the park's Wildlife Encounter Pavilion. *http://www.dep.state.fl.us/secretary/news/2005/03/0301_03.htm* *http://www.progress-energy.com/aboutus/news/article.asp?id=11322*
6. Clean Air Now Solar Hydrogen Stations in Southern California The Clean Air Now (CAN) solar hydrogen demonstration project started in August 1994 with funding from industry partners, the US DOE, and SCAQMD. The first PV-electrolysis-hydrogen system was located at a Xerox Corporation facility in southern California. The first hydrogen vehicles were Ford Ranger trucks converted to hydrogen ICE engines. The goal of the CAN project is a hydrogen corridor in southern California that extends to the Sunline Transit Agency hydrogen station in Palm Desert, which opened in April 2000. In a related project, the transit agency hosts the PV-electrolysis Schatz Hydrogen Generation Center that opened in 1994 and was retrofit in 2001–2002. *http://www.cleanairnow.us/index.html*
7. Renewable Electrolysis Fueling Station in Taos, New Mexico Hydrogen is generated via wind and solar-powered electrolysis. This site is an "eco-retreat" called Angel's Nest in Taos, New Mexico. The hydrogen system was privately purchased and can produce 2kg of hydrogen per day. The hydrogen will be used in fuel cells for off-peak power for the site and to fuel two hydrogen-powered Hummers at the retreat.

Table 1: **U.S. and International Renewable Hydrogen Demonstration Projects** (CONTINUED)

U.S. PROJECTS
Hydrogen Production from Renewables-Based Electrolysis
8. Honda Motors Co. Hydrogen Fueling Station The Honda Research and Development Center in Torrance, California has a vehicle fueling station that uses solar-powered electrolysis with grid backup. The station opened in July 2001. *http://world.honda.com/news/2001/c010710.html*
9. Toyota USA Headquarters Hydrogen Fueling Station Toyota USA Headquarters in Torrance, CA uses a Stuart Energy hydrogen fueling station powered by renewable electricity. The system generates 24 kg of hydrogen per day. This station opened in early 2003, and Toyota plans to open 5 more refueling stations in California.
Hydrogen Production from Biomass
10. Sierra Nevada Brewing Company in Chico, CA Sierra Nevada Brewery recently finished a project to generate hydrogen from methane, derived from anaerobic digester gas that is a byproduct of the beer brewing process. The hydrogen is used in four Fuel Cell Energy 250-kW fuel cells to generate electricity onsite. More information on this project is available in the featured projects section below. *http://www.energy.ca.gov/distgen/installations/sierra.html* *http://www.corporate-ir.net/ireye/ir_site.zhtml?ticker=FCEL&script=412&layout=-6&item_id=736791*
11. Chicago Ethanol-to-Hydrogen Station 2 million dollars was awarded to the city of Chicago in a federal energy and water appropriations bill passed in November 2005. The money will fund a liquid ethanol-to-hydrogen station to fuel 5 fuel cell vehicles. Construction is scheduled to begin sometime in 2006.
INTERNATIONAL PROJECTS
Hydrogen Production from Renewables-Based Electrolysis
12. Prince Edward Island Wind-Hydrogen Village Project Prince Edward Island is home to the Atlantic Wind Test Site, and 5 percent of the island's electricity is currently generated from wind. This project will integrate hydrogen production, storage, and use in a range of applications including a hydrogen energy station and power production for buildings at the test site. The project was announced in spring 2005 and will be led by Hydrogenics Corporation and Prince Edward Island Energy Corporation. *http://www.gov.pe.ca/envengfor/index.php3?number=1007450&lang=E*
13. Wind-to-Hydrogen Feasibility Study in Pico Truncado, Argentina Pico Truncado, Argentina currently receives more than half of its electricity from wind power and has a large untapped wind resource. An Argentine oil company is funding a feasibility study of a $19 billion, internationally financed, wind-to-hydrogen electrolysis facility for hydrogen export. The city has made investments in a hydrogen plant for local transportation applications. *http://www.washingtonpost.com/wp-dyn/content/article/2005/05/14/AR2005051401020.html* *http://www.scidev.net/News/index.cfm?fuseaction=readNews&itemid=897&language=1*
14. Renewable-Powered Electrolysis in Iceland Abundant geothermal and hydropower resources in Iceland are used to produce the majority of the country's electricity, and the government has been moving forward with a plan to use this renewable electricity for hydrogen generation with the eventual goal of an all-hydrogen transportation sector. Currently, the majority of Iceland's hydrogen is produced via electrolysis from renewables to make ammonia for fertilizers. In 2003, a hydrogen fueling station opened in Reykjavik to fuel the city's buses.

Table 1: **U.S. and International Renewable Hydrogen Demonstration Projects** (CONTINUED)

INTERNATIONAL PROJECTS
Hydrogen Production from Renewables-Based Electrolysis
15. Wind-Electrolysis Hydrogen at Mawson Research Station, Antarctica The Mawson Research Station in Antarctica received funding from the Australian Greenhouse Office to demonstrate hydrogen production from on-site wind power. The station's two wind turbines became operational in 2004. The hydrogen and fuel cell system will be installed during the 2005-2006 summer season. The fuel cell will be used to generate electricity and heat for the site. *http://www.aad.gov.au/default.asp?casid=13736*
16. Wind-Electrolysis System at Stralsund, Germany This renewable hydrogen project is a university research project in Stralsund, Germany. This project uses a 100 kW wind system and electrolyzer to test the performance of intermittent operation. *http://www.ieahia.org/case_studies.html*
17. Wind-Hydrogen System on Utsira Island, Norway The small (10 household) community of Utsira, Norway installed a wind-hydrogen electricity facility in 2004. The hydrogen plant is used to provide power when the wind is not available, and storage capacity allows the plant to operate for two full days without wind. *http://www.h2cars.biz/artman/publish/article_506.shtml*
18. Clean Urban Transportation Europe (CUTE) Project The goal of this project is to use hydrogen for public transportation systems in nine European cities: Amsterdam, Barcelona, Hamburg, London, Luxembourg, Madrid, Porto, Stockholm, and Stuttgart. The method of hydrogen production varies from site to site, but four of the cities will produce hydrogen via electrolysis, some from renewable energy. *http://europa.eu.int/comm/energy_transport/en/prog_cut_en.html#cute*
19. Integrated Wind-Solar-Hydrogen System at the Hydrogen Research Institute, Quebec This system was installed for research purposes at the Hydrogen Research Institute at the University of Quebec in Trois-Rivieres and has been in operation since May 2001. The system consists of a 10 kW wind generator, a 1 kW PV system, a 5 kW electrolyzer, and a 5 kW fuel cell. There is also a battery for short-term energy storage. Researchers have been testing and monitoring the integrated system.
20. PHOEBUS PV-Hydrogen Demonstration at the Julich Research Center, Germany This demonstration project powers the central library of the Julich Research Center in Germany. The system began operation in 1997 and consists of a 43 kW PV array for electricity production and an electrolyzer-hydrogen storage-fuel cell system for off-peak power. Initially, an alkaline fuel cell was part of the system, but this was later switched to a PEM fuel cell after poor performance.
21. Residential PV-Hydrogen System in Zollbruck, Switzerland This system consists of a 7 kW grid-connected PV array with battery backup and an electrolyzer for hydrogen production. The PV electricity output is primarily used to charge the battery or feed into the grid, though manual control of hydrogen production is possible. The hydrogen can be used for vehicle fueling or in appliances such as a stove and laundry. The system was installed in 1991 and was privately funded by the homeowner.
Other New Hydrogen Technology Demonstrations
22. Solar to Hydrogen Facility in Rehovot, Israel This facility uses 64 existing solar concentrating mirrors at the Weizmann Institute of Science to heat zinc oxide, which will separate into oxygen and gaseous zinc. When pure zinc is condensed to a powder form, it will react with water to produce hydrogen, and the zinc oxide byproduct can be reused. Results of a large-scale test of this process were recently completed and presented in 2005. *http://80.70.129.162/site/en/weizman.asp?pi=371&doc_id=4210*

Table 1: **U.S. and International Renewable Hydrogen Demonstration Projects** (CONTINUED)

INTERNATIONAL PROJECTS
Other New Hydrogen Technology Demonstrations
23. Solar-Powered Landfill Gas Conversion in Saskatoon, Canada This is a demonstration project that uses solar concentrators to produce electricity and hydrogen from landfill gas. Canada's SHEC Labs runs the project. A prototype system has been operational for 1,200 hours.
24. Hydrogen Solar Tandem Cell Demonstration The British company Hydrogen Solar owns the rights to their Tandem Cell technology, a device used for photoelectrochemical water splitting. The technology was developed along with Michael Gratzel of the Swiss Federal Institute of Technology. The Tandem Cell is a device that efficiently produces hydrogen by maximizing the surface area of a catalyst cell and combining it with a photovoltaic device that boosts the number of electrons available to split water. The device has converted sunlight to hydrogen with an efficiency of 8%. Hydrogen Solar was awarded funding from the BOC Foundation to demonstrate a Tandem Cell array over a six-month period at the Beacon Energy Ltd site at West Beacon Farm, Leicestershire. *http://www.hydrogensolar.com/October5.html*
25. 2008 Beijing Olympic Games The Hydrogen Transportation Partnership Beijing 2008 is a group that is organizing hydrogen and fuel cell vehicle demonstrations at the 2008 Beijing Olympic Games. The US DOE joined the partnership and is soliciting proposals for renewable hydrogen demonstration projects for the event.

Featured Hydrogen Demonstration Projects

This section provides more detail on four example renewable hydrogen demonstration projects in the U.S. These projects are being highlighted because we believe they represent models for state action that can be replicated in other states. In each case, these projects are serving to demonstrate the viability of hydrogen technologies working in concert with renewable energy sources. The featured projects are:

1. Hydrogen Fueling Station at the Department of Public Works in Burlington, Vermont
2. Wind-to-Hydrogen Demonstration in Minnesota
3. High Temperature Fuel Cells at the Sierra Nevada Brewing Co. in Chico, California
4. Residential Solar-to-Hydrogen System in New Jersey

HYDROGEN FUELING STATION AT THE BURLINGTON, VERMONT DEPARTMENT OF PUBLIC WORKS

This vehicle fueling station in Burlington, Vermont is a collaborative effort between EVermont, a non-profit agency that promotes the development and use of clean vehicles in Vermont, and the Distributed Energy Systems subsidiaries Northern Power Systems and Proton Energy. Hydrogen will be generated using a grid-connected electrolyzer with a capacity of up to 12 kg of hydrogen per day. A large portion of local grid electricity is generated from renewables, including a wind turbine located adjacent to the site of the fueling station at the Burlington Vermont Department of Public Works.

Hydrogen Production Method:
Electrolysis via renewable grid electricity

Location:
Burlington, Vermont

Production Capacity:
12 kg of hydrogen per day

Total Project Cost:
Approximately $2 Million

Funding Sources:
US Department of Energy, multiple project partners

EVermont was awarded just under $1 million for the project from the US DOE's Hydrogen, Fuel Cells, and Infrastructure Program beginning in October 2004. Additional cost-shares totaling $1 million are being provided by project partners Northern Power, Proton Energy Systems, and Air Products and Chemicals.

The primary components of the fueling station are a Proton Energy Hogen H Series electrolyzer and an Air Products Series 200 fueling station. The system can store up to 12 kg of compressed hydrogen at one time. Hydrogen will be produced using grid electricity from the Burlington Electric Department, which generates approximately 40 percent of its electricity from renewables. The BED will donate the renewable credits from the adjacent windmill toward the cost of electricity purchased to produce hydrogen.

This hydrogen fueling station will test the performance of the system components in an outdoor environment and under the cold winter temperature conditions of the northeast US. The first vehicle to utilize the hydrogen station will be a 2005 Toyota Prius converted to run on hydrogen by Quantum Technologies of Irvine, CA. The fueling station and vehicle are expected to be operational by summer 2006. Testing will take place for one year, with further operation dependent on available funds.

If purchasing off the grid as planned, the cost to produce hydrogen at this fueling station is estimated to be $8 to $12/kg. However, the impact of heating the enclosed station during the winter is significant at such small-scale production and can increase the operational costs by about 40 percent.

Additional Information:

- **Northern Power Press Release** from March 2005
- **Distributed Energy Systems Press Release** from March 2005
- **EVermont Project Page**

Demonstration site at the Vermont Department of Public Works in December 2005. This picture shows the platform ready for equipment to be installed.

WIND-TO-HYDROGEN DEMONSTRATION IN MINNESOTA

Hydrogen Production Method:
Electrolysis via wind turbine

Location:
Morris, Minnesota

Production Capacity:
1.65 MW wind turbine, 400 kW electrolyzer

Total Project Cost:
Approximately $2.8 million

Funding Sources:
University of Minnesota, Legislative Commission on Minnesota Resources

This is one of several projects being conducted at the University of Minnesota's Renewable Energy Research and Demonstration Center at Morris, Minnesota. Researchers at the Center will install and test an integrated wind—hydrogen system to produce hydrogen via electrolysis. One goal of the project is to demonstrate the feasibility of hydrogen storage for off-peak wind energy.

$2 million in funding for the wind demonstration project came through the University of Minnesota's Initiative for Renewable Energy and the Environment over a three-year period (2003–2005). $800,000 was leveraged from the Legislative Commission on Minnesota Resources for the hydrogen portion of the project, and Xcel Energy has provided equipment cost sharing. Partners additionally include the Upper Midwest Hydrogen Initiative and member companies, Windustry, and the National Renewable Energy Lab.

The wind turbine is a Vestas NM 82 with a rated capacity of 1.65 MW that is expected to produce 5.6 million kWh of electricity annually at this site. The turbine was installed in early 2005 and is now supplying power to the University of Minnesota. Funding has been received for the hydrogen portion of the project, which is scheduled to begin in late 2005 or early 2006. This phase will incorporate a 400 kW electrolyzer, hydrogen storage tanks, and an internal combustion engine that will use the hydrogen for "on-demand" electricity.

Additional goals of this project are to demonstrate the feasibility of replacing natural gas with renewable hydrogen in fertilizer production and to demonstrate the use of a hydrogen—natural gas mixture to fuel a gas turbine for large scale wind hybrid systems.

Additional Information:

- **Institute for Renewable Energy and the Environment Home Page**
- **Renewable Energy Research and Demonstration Center at Morris**

Construction of the 1.65 MW wind turbine at the Morris research center.

SIERRA NEVADA BREWERY IN CHICO, CALIFORNIA

Hydrogen Production Method:
Digester gas from brewing process

Location:
Chico, California

Production Capacity:
Fuel for one 250 kW fuel cell (approx. capacity)

Total Project Cost:
$7 million over five years

Funding Sources:
California Energy Commission, U.S. Department of Defense

The Sierra Nevada Brewery in Chico, California is producing hydrogen from byproducts of the company's beer brewing process. Beer brewing uses a two-step anaerobic and aerobic digester process that produces methane, which is then captured and reformed into hydrogen. The brewery has installed four 250 kW fuel cells that run off a combination of the renewable hydrogen and natural gas.

This project was dedicated in July 2005. The total project cost for the first five years is approximately $7 million, including installation costs and operation and maintenance for the hydrogen production system and the fuel cells. The Sierra Nevada Brewery received $2.4 million in funding through the California Public Utility Commission Self Generation Incentive Program and an additional $1 million through the U.S. Department of Defense Climate Change Fuel Cell Program. Given these initial subsidies, project managers expect a payback of less than five years, which reflects an electricity cost savings of about $400,000 per year.

The four 250 kW fuel cells are high-temperature molten carbonate fuel cells from FuelCell Energy Inc. They will provide almost 100% of the facility's baseload power, and the waste heat will be collected as steam and used for the brewing process as well as other heating needs onsite. The fuel cells initially ran off of natural gas, but the brewery hopes to displace 25–40% of the natural gas use with the digester gas, depending on what type of beer is being brewed.

Additional Information:

- **Fuel Cell Energy Press Release** from July 2005
- **Self Generation Incentive Program**
- **Sierra Nevada Brewing Company**

Four 250 kW molten carbonate fuel cells power the Sierra Nevada Brewery

RESIDENTIAL SOLAR TO HYDROGEN SYSTEM IN NEW JERSEY

Hydrogen Production Method:
Electrolysis via photovoltaic system

Location:
East Amwell, New Jersey

Production Capacity:
Sized for Residential Home

Total Project Cost:
Unknown

Funding Sources:
New Jersey Board of Public Utilities

This system is being developed for a residential home in East Amwell, New Jersey. A photovoltaic system will be the primary electricity source, and excess electricity will be used to generate hydrogen via electrolysis for off-peak fuel cell power. This system will operate independent of the grid, although the home is connected to the grid for backup purposes. Waste heat from the fuel cell will additionally be used to supplement a geothermal heat pump.

This demonstration project was allocated funds in 2003 by the New Jersey Board of Public Utilities, through its Renewable Energy and Economic Development Grant program. The $225,000 grant was awarded to Resource Control Corporation of Moorestown, New Jersey.

The photovoltaic system is installed and operational, but the hydrogen component of this project is currently on hold pending approval for hydrogen storage devices in a residential neighborhood. In the fall of 2005, the East Amwell Town Council approved the installation, pending construction code reviews. Current approval is required from the Department of Consumer Affairs, which does not have precedent for pressurized hydrogen storage tanks in a residential neighborhood. The gaseous hydrogen storage is proposed to consist of ten 1,000 gallon tanks that would contain the approximate energy equivalent of 20 gallons of propane.

RECOMMENDATIONS

Advances in basic science and engineering, combined with increasing public concern about energy policy, are expanding the potential of hydrogen-based and other clean energy technologies. As a consequence, new interest and increased activity at the state and national level are emerging to explore the expanded commercialization of hydrogen and fuel cell systems and applications.

Recognizing these trends, the Clean Energy Group (CEG), in support of the Public Fuel Cell Alliance (PFCA) project, commissioned this study in order to better understand the current state of hydrogen technologies and the opportunities to promote new activities. We offer these recommendations to help states consider the potential implementation of complementary policy actions to promote hydrogen production from renewable resources. We recognize that there is not a single set of recommendations that will be suitable for each state. However, taken together, we believe that the recommendations offered here provide a comprehensive approach to facilitate the emergence of a hydrogen economy. It is our hope that these observations and recommendations can serve as a starting point for in-depth discussions leading to state-specific action plans and stakeholder engagement processes.

The early projects profiled in this report represent an important opportunity to both gain experience and begin to create linkages between existing networks of activities with regard to hydrogen. Accelerating these efforts will provide important “learning-by-doing” benefits, and action from state clean energy funds and other stakeholders can help develop this knowledge base for renewable hydrogen production.

There is an opportunity to accelerate the positive trends with regard to hydrogen production and its linkages to clean energy technologies. Particularly, we’d like to emphasize the uses for transportation could be linked to stationary power generation, as these have been less thoroughly funded than transportation sector programs and offer potentially more attractive near-term economics. Opportunities to deploy and demonstrate new roles for hydrogen within the stationary power system should be more fully explored for their combined potential energy efficiency, emissions reduction, energy security, and grid reliability/support benefits.

The recommendations below focus primarily on action steps that could be implemented by state clean energy funds, economic development offices and other technology-specific state initiatives. Because of their unique combination of resources, these partners are able to combine financial incentives, policy expertise and technical resources to implement and support effort that could provide important learning-by-doing benefits to better inform deployment strategies.

We have assembled several recommendations for consideration by those key stakeholders that have an interest in developing strategies for promoting renewable hydrogen technologies and projects. While it is clear that there is no simple, “one-size-fits-all” program for state action, these are intended to serve as a starting point for in-depth discussions that can lead to state-specific action plans and stakeholder engagement processes.

Our recommendations include:

- **Dedicate Significant Funding:** State clean energy funds that currently support a broad suite of renewable energy technologies can commit significant, dedicated funding to develop action plans and programs that address the very real economic and technology barriers facing the production of hydrogen from renewable energy sources. In addition, there are significant opportunities to establish federal-state funding partnerships with agencies such as DOE, DOD and DHS that can leverage limited funding for hydrogen projects that use renewable energy technologies.
- **Demonstrate The Viability of Hydrogen Storage and Production for Critical Applications:** State clean energy funds and other public interest organizations have the opportunity to support projects that can demonstrate the viability of using hydrogen storage and energy conversion in critical applications, such as telecommunications and backup power, where on-site storage of hydrogen provides important power quality and security benefits.
- **Visibly Link Hydrogen Production and Clean Energy Technologies:** Wind, photovoltaics and other projects that include clean energy technologies should be promoted as the preferred source of hydrogen production. Supporting projects that highlight the capability of producing hydrogen on-site from these sources will serve an important “ambassador” role, engendering important local

and public support for hydrogen technologies. These projects can also support the acceptance of natural gas as an important transition fuel. Many states that currently support other clean energy technologies can seek opportunities to develop hybrid projects, linking together energy generation with hydrogen production and storage.

- **Establish Incentives for High-Value, On-Site Applications:** Financial incentives that target specific applications of hydrogen technology can encourage both private and public-sector players to deploy hydrogen and fuel cell technologies. High-value and niche applications for production and use of hydrogen (such as backup power and battery replacement) from renewable sources may lead to self-sustaining markets, important learning-by-doing benefits, and increased public acceptance.

- **Proactively Address Regulatory Incentives:** Advanced energy technologies can best be promoted with forward-thinking regulatory policies. Many states have implemented regulatory preferences and incentives (such as standby charge exemptions and net metering policies) that recognize and accommodate the public preference for and benefits from fuel cell, hydrogen and clean energy technologies. The regulatory strategies used by these early leaders can be replicated in other states. If hydrogen is to fulfill its role in a clean energy future, it will certainly be in conjunction with clean energy technologies that can operate in a distributed energy context. Currently, many regulatory barriers prevent the wide-scale adoption of clean distributed generation and limit the ability to store hydrogen on-site. These can be critical components of distributed generation projects that rely on hydrogen derived from renewable resources.

- **Accelerate Private Investment:** Successfully deploying hydrogen technologies will require significant investment from the private sector. The introduction of new technologies entails crossing what has come to be called “the valley of death”—the need for capital investments to take promising technologies from the invention and technology validation stage to the point of initial demonstration, field testing, and commercialization. These early investments can be accelerated with preferential tax treatment and other incentives to judiciously use public resources to assist and share risks with industry to develop new energy solutions. Florida, for example, has proposed significant tax benefits that could accelerate ongoing investments by Fortune 100 companies such as the recent investments by Sprint in fuel cell systems. States should consider enacting similar favorable tax policies and exemptions for projects developing hydrogen from renewable resources.

- **Develop Compelling Communications Strategies:** The potential use of hydrogen outside of the industrial sector has been riddled with public misperceptions and lack of awareness of its significant benefits. In recent years, many states have conducted sophisticated consumer and stakeholder research that has resulted in new communications campaigns to increase public understanding and support for clean energy technologies. Many states, for example, recently joined together to develop and fund a “Clean Energy: It’s Real, It’s Here, It’s Working. Let’s Make More” branding campaign. This kind of proactive communications strategy could yield tremendous results for the hydrogen sector, helping to organize currently disparate enthusiasm for hydrogen with a single, compelling message.

CONCLUSION

The promise of a clean and sustainable energy future lies in technologies that capture natural energy flows as well as in technologies that store and distribute that energy effectively. Hydrogen pathways that are coupled with low carbon energy sources remain among the most promising of long-term options for providing sustainable energy with low fuel-cycle emissions of greenhouse gases and air pollutants.

Hydrogen, fuel cell, and renewable energy technologies have developed rapidly in recent years, and the introduction of commercial systems is accelerating. Technological challenges remain, particularly for hydrogen in transportation markets, but growing needs for improved energy efficiency, greater energy security, and reduced emissions are continuing to highlight the need to explore promising longer-term options for these goals. These farsighted energy R&D efforts should be complemented with other near-term strategies to achieve more modest but immediate steps toward societal goals, particularly where key synergies can be found (e.g. with more traditional combined heat and power systems being integrated into utility grids in advance of stationary fuel cells, hybrid vehicle propulsion systems development to help enable future fuel cell vehicles, etc.).

While the projects profiled here are mostly early-stage demonstrations, they indicate that sensible strategies are emerging for integrating hydrogen technologies into stationary power systems. As a result of federal and state policy initiatives and through the efforts of the PFCA, Clean Energy States Alliance (CESA), and other multi-state collaborative efforts, we anticipate that the topic of producing hydrogen from renewable resources will continue to receive significant attention. We hope that this report will serve to inform and advance these ongoing efforts for further clean energy development activities among state clean energy funds and other regional partners.

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Appendix A: Summaries of Notable State Hydrogen Programs

REVIEW OF PRIMARY STATE HYDROGEN ACTIVITIES AND INCENTIVE PROGRAMS

Hydrogen research, development, demonstration, and incentive activities that are primarily being initiated at the state level are reviewed below. These efforts in some cases extend to the regional level and are therefore grouped regionally.

In addition to California's activities, New York, Florida, Connecticut, Michigan, Ohio, and Texas are enacting bold initiatives such as the "New York Hydrogen Highway," "H2 Florida," "NextEnergy" in Michigan, "Fuel Cells Texas," and the "Ohio Fuel Cell Coalition" to garner private sector and federal investment for the development of these industries. With significant federal funding now being allocated for hydrogen and other clean energy system development, and with venture capital markets taking large positions in the clean energy sector, states are competing vigorously to position themselves to compete for these resources.

California

Under Governor Schwarzenegger, California is charting a bold course for the development of hydrogen infrastructure and the introduction of hydrogen-powered vehicles. Building on the state's low-emission vehicle program and "zero-emission vehicle mandate," Governor Schwarzenegger adopted an Executive Order in 2004 that provides considerable momentum for hydrogen R&D activities in California, with a strong emphasis toward expanded deployment efforts in the near- and medium-term. The California Fuel Cell Partnership (CAFCP) and California Stationary Fuel Cell Collaborative (CASFCC) are key organizations that are expected to take part in hydrogen activities in California, along with State and regional agencies, universities and governmental laboratories, and other groups.

The main elements of the Governor's recent "California Hydrogen Highway Network" Executive Order include (State of California, 2004):

- Designation of the state's 21 Interstate highways as the "California Hydrogen Highway Network;"
- Development of a "California Hydrogen Economy Blueprint Plan" by January 1, 2005, for the "rapid transition to a hydrogen economy in California" (to be updated biannually);
- Negotiations with automakers and fuel cell manufacturers to "ensure that hydrogen-powered cars, buses, trucks, and generators become commercially available for purchase by California consumers, businesses and agencies;"
- Purchase of an increasing number of hydrogen powered vehicles "when possible" for use in California's state vehicle fleets;
- Development of safety standards, building codes, and emergency response procedures for hydrogen fueling stations and vehicles;
- Provision of incentives to encourage hydrogen vehicle purchase and the development of renewable sources of energy for hydrogen production; and
- Ultimately planning and building a significant level of hydrogen infrastructure in California by 2010, so that "every Californian will have access to hydrogen fuel, with a significant and increasing percentage produced from clean, renewable sources."

The California Hydrogen Blueprint Plan (California Environmental Protection Agency, 2005a) was developed during the second half of 2004 and released in March of 2005. The plan calls for the implementation of the "California Hydrogen Highway Network" per the Governor's Executive Order. The plan and associated reports represent several months of effort by a senior review committee, the Governor's executive officers team, an implementation advisory panel, five "topic teams" each composed of 30 to 50 industry, academic, and governmental experts, and additional consultant work. The topic teams addressed the following topics: "Public Education," "Economy," "Societal Benefits," "Implementation," and "Blueprint and Rollout Strategy." Each team produced an extensive report that was then used in compiling the final blueprint plan.

The plan calls for a phased approach whereby 50 to 100 hydrogen stations would be in place during Phase 1, along with approximately 2,000 vehicles. Phase 1 is a five-year time period from 2005 to 2010. Phase 2 would be marked by an increase in hydrogen refueling stations to 250, along with up to 10,000 hydrogen-powered vehicles. Finally, Phase 3 would entail an expansion of the vehicle fleet to 20,000 as the last precursor to full-scale commercialization. The timing of Phases 2 and 3 would depend upon technological developments and the outcome of biennial reviews. The blueprint emphasizes the following benefits associated with the pursuit of this plan: energy diversity, security, environmental, economic development, and education (California Environmental Protection Agency, 2005a).

The blueprint plan makes specific reference to the need for renewable hydrogen as part of the California strategy by recommending a "renewable portfolio standard" for hydrogen production that would parallel the standard for renewable electricity production. The plan recommends a requirement that 20% of hydrogen should be produced renewably in the initial stages of the introduction of hydrogen-powered vehicles, with the percentage increasing thereafter (California Environmental Protection Agency, 2005b).

New York

The State of New York has been working on a "hydrogen roadmap" in an effort led by the New York State Energy Research and Development Agency (NYSERDA) and its contractor Energetics, Inc. Several "vision" workshops were held around the state during Fall 2004 and Spring 2005, to garner feedback from the public and invited experts. The hydrogen roadmap plan for New York was released in October of 2005.

The New York roadmap plan is similar to the California plan, and it calls for a multi-phase approach to usher in the beginnings of a hydrogen economy in NY. It addresses both transportation and stationary power applications of hydrogen and fuel cell technologies. Phase I of the plan consists of "high profile demonstrations," designed to further R&D, raise public awareness, and establish codes and standards and supportive policies. Phase II would consist of "market entry" and would focus on "the three C's: cities, clusters, and corridors." Phase II would focus on reducing costs and developing the basic elements of the New York hydrogen network. Finally, Phase III would be a full commercialization phase where various clusters of activity would be linked in to a statewide network and where the government role could be stepped back (NYSERDA, 2005).

New York has various hydrogen projects underway and planned, including stationary fuel cell demonstrations on Long Island, a few Honda FCVs that are being leased by the State in Albany, and a plan for six to ten (initially) heavy-duty hydrogen ICE conversion vehicles in Buffalo. The project involves Praxair, the State University of New York (SUNY) Buffalo, and the Niagara Frontier Transit Authority. The vehicles will refuel with by-product hydrogen from chlor-alkali production, as that area benefits from inexpensive hydropower along the Niagara River (Love, 2005).

In addition to the roadmap activity, New York is also engaging in hydrogen and fuel cell codes and standards review, education and outreach (e.g., "teaching the teachers"), and technology R&D activities.

Florida

In Florida, Governor Jeb Bush launched the "H2 Florida" initiative in July 2003, and in March 2005 he "broke ground" on a "Hydrogen Highway" initiative similar to California's. Approximately $15 million in state funds for hydrogen projects has been proposed.

Florida's statewide programs are intended to accelerate the development and deployment of hydrogen technologies in Florida, with multiple goals in mind. These goals include:

- Diversifying Florida's economy by stimulating corporate investment;
- Demonstrating hydrogen energy technologies;
- Establishing public-private partnerships;
- Recruiting and supporting hydrogen technology companies in Florida;
- Demonstrating new business models for corporate revenue and profit;
- Increasing energy security and independence; and
- Keeping Florida's air clean.

As part of this initiative, Florida has launched the "Florida Hydrogen Business Partnership," which is composed of over 20 companies. This is an effort to "establish Florida as the center of hydrogen technology commercialization in the Americas." The partnership currently lists 22 member companies that include fuel cell companies, hydrogen gas suppliers, large energy companies, and electric utilities (Florida Energy Office, 2005).

The Partnership finalized the "Florida Hydrogen Energy Roadmap" on March 23, 2005, which supports a "Florida Hydrogen Energy Technologies Act" proposed by Gov. Bush at a recent hydrogen station groundbreaking. This legislation calls for financial incentives, expanded demonstration projects, and a uniform siting standard for businesses that invest in hydrogen in Florida (FDEP, 2005a).

The Florida Hydrogen Energy Roadmap calls for many of the familiar measures that are being discussed by state and federal governments in the U.S. and abroad:

1) A portfolio of demonstration projects across sectors;
2) Tax and financial incentives for both demonstration and commercial activities;
3) Public-private partnerships to share risks;
4) Governmental incentive (rather than regulation) policies;
5) State and local technology procurement programs;
6) Targeted infrastructure development and streamlined siting procedures;
7) Coordinated academic research in collaboration with industry; and
8) Public education and outreach programs.

The plan goes as far as to suggest specific tax incentives and measures, and it reports that five hydrogen refueling stations are expected in metropolitan Orlando by 2007, with fuel cell-based electrical generation capacity on-line "to exceed 500 kW" (FDEP, 2005b).

In terms of demonstration and pilot project activities to-date, Florida's efforts are concentrated in the Orlando area. Five Ford Focus FCVs will be demonstrated in North Orlando with refueling infrastructure provided by BP in a program funded under the U.S. Department of Energy's "Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project" (Barber, 2005). In a second project, eight Ford E-450 shuttle vehicles will be deployed at the Orlando airport starting in 2006. These hydrogen combustion vehicles use a 6.8-liter V-10 engine and about 26 kilograms of hydrogen, stored at 5,000 pounds per square inch of pressure, to produce a driving range of about 150 miles (McCormick, 2005).

Finally, two airport "tug" vehicles will be converted to combust hydrogen and then will be tested at the Orlando International airport in 2006. The Florida Department of Environmental Protection, Delta Airlines, Ford Motor Company, and TUG Technologies are involved in the project. The vehicles will initially be refueled using a mobile refueling unit and possibly with a more permanent station especially if additional hydrogen-powered tugs are deployed (Barber, 2005; Hydrogen Now, 2005).

The Florida Energy Office and the Florida Department of Environmental Protection are the state agencies most involved in the H2 Florida initiative. The energy office coordinates hydrogen research and demonstration activities in the state and manages the "Florida Hydrogen Initiative, Inc." This nonprofit organization has been developed to broker demonstration projects and to sponsor research in hydrogen production, storage, and use. At present, the Florida Department of Transportation is apparently not playing an active role in the H2 Florida initiative, but the agency may become more involved as demonstration project activities become more extensive.

Michigan

Michigan has been aggressive in trying to attract existing fuel cell and other clean energy companies from outside the state. The organization heading this effort is "NextEnergy," a state-funded, nonprofit entity authorized to stimulate the development of advanced power systems with a strong focus on fuel cells. NextEnergy's stated mission is to "make Michigan a world center of excellence for alternative energy technology education, research, development, and manufacturing." Within this broad mandate, there are two main priorities at present:

- Construction of the NextEnergy Center; and
- Educational programs—$1 million has been set aside to disburse to several Michigan universities to create curricula in alternative energy technologies to help produce the "engineer of the future."

Industry recruitment is another priority and will likely rise in importance once the building nears completion. NextEnergy has a goal of creating five new advanced power technology companies within the state during 2003. They expect to work with existing companies both outside Michigan and outside the country in recruiting companies and partnerships (Michigan NextEnergy, 2003).

Although the scope of NextEnergy includes all advanced power technologies, fuel cell commercialization and deployment will be its primary focus. The NextEnergy Program is intentionally broad and will include efforts for both stationary and transportation-related fuel cells. The Center itself will be powered by a stationary fuel cell system. However, with the automobile industry located nearby, there is a strong long-term interest in fuel cells for transportation.

Other State Hydrogen Programs

Colorado

The Fuel Cell Research Center has developed a $12 million fuel cell demonstration program, leveraged from $2 million in public funding from a petroleum violation escrow account. The center was launched in 2004 at the Colorado School of Mines in Golden, Colorado (U.S. DOE, 2004).

Connecticut

The Connecticut Clean Energy Fund has a five-year budget of $100 million to support renewable energy and fuel cells. This included $22 million in 2002 and a somewhat scaled-back 2003 budget of $16 million. Within this program, the Fuel Cell Initiative (CCEF-FCI) provides loans, grants, and equity investment for the demonstration and commercialization of fuel cells. The CCEF-FCI disbursed $9 million in funds in 2002, up from$5 million in 2001, demonstrating the attention that fuel cell industry development is receiving under this program. The primary focus of this program is fuel cells for stationary applications (Connecticut Clean Energy Fund, 2004).

Hawaii

Hawaii has received several million dollars in federal funding for hydrogen research, development, and demonstration projects. Much of this funding has been directed toward the Hawaii Natural Energy Institute at the University of Hawaii Manoa campus (Honolulu, Oahu) and the Natural Energy Lab of Hawaii Authority (NELHA in Kailua-Kona, Hawaii). A "DER Gateway" has been constructed at the NELHA site near the Kona airport on the Big Island, and the two organizations are expecting to collaborate on hardware demonstration and testing activities at the DER Gateway and other locations around the islands.

Massachusetts

Massachusetts has a hydrogen roadmap planning activity underway and several additional new hydrogen and fuel cell-related initiatives. The state is citing a potential demand for fuel cells of $46 billion by 2011 and its high "density" of over 80 active fuel cell companies in its push to attract fuel cell industrial activity to the state. The Massachusetts Hydrogen Coalition is leading this effort. The Coalition lists "job creation," "energy security," "clean transportation," and "high mobility power" as primary drivers for the state to lead these efforts.

On June 14, 2005, the Coalition proposed seven initiatives to significantly expand the hydrogen and fuel cell industry in Massachusetts. These initiatives include developing the Massachusetts "Clean Energy Corridor," establishing a "Hydrogen and Fuel Cell Center," establishing a "Clean Energy Export Program," greater hydrogen and fuel cell education and outreach, increased state resource allocation and procurement, and establishing appropriate tax and financial incentives. As a first step, the Coalition will work collaboratively with representatives from state agencies, institutions, universities, and industry leaders to develop the Massachusetts Hydrogen Roadmap (AIADA, 2005).

Ohio

The Ohio Fuel Cell Initiative is a $103 million program that is part of Ohio's $1.6 billion "Third Frontier Project" aimed at supporting high-tech sectors in Ohio. Launched on May 9, 2003, there are two main components to the initiative:

1) Financing for company expansion ($75 million budget over three years), and

2) R&D support ($25 million budget over three years).

There is also a fund of $3 million dedicated to retraining workers. The Ohio program stands out from other states in its ambitious plan to dedicate 75 percent of its resources to provide financing for fuel cell companies to expand their manufacturing operations. The program goal is economic development for Ohio. A few years ago, a study by Battelle found that there was already a core of high tech companies, universities, and government labs in Ohio. This study resulted in the decision to launch the Third Frontier program to grow high-tech industry in Ohio where there are as many automotive suppliers (McKay, 2003).

Washington

Building on initial alternative fuel legislation passed in 2003, efforts in Washington are highlighted by a recent effort to pass three bills with implications for hydrogen/fuel cells and other alternative fuels., Three bills co-sponsored by Representatives Brian Sullivan and Jeff Morris passed by the Washington State House Technology, Energy and Communications Committee on February 22, 2005, and they proceeded to fiscal committees for funding appropriation. These include:

1) House Bill 1645 that would exempt school districts from the state's 28-cent-per-gallon special fuel tax on the bio-fuel portion of the fuel in their school buses, if they use more than a 20 percent blend;

2) House Bill 1646 that would encourage the alternative fuels industry through tax exemptions on sales and use tax, business and occupation (B&O), and property taxes for six years after building manufacturing facilities; and

3) House Bill 1647 would provide tax incentives for using and purchasing alternative fuel vehicles, alternative fuel refueling equipment, and alternative fuel.

All three bills have benchmarks to assess effectiveness. They also build on legislation passed two years ago in one of the nation's first state-level alternative fuels incentives packages (Sullivan, 2005).

U.S. Regional Hydrogen Programs

In addition to the above state-level efforts to promote the use of hydrogen and fuel cells, there also are a few noteworthy regional efforts that are banding states together to leverage their activities. These efforts include the Public Fuel Cell Alliance (PFCA) and a new effort that has been launched in the Northern Plains region known as the Upper Midwest Hydrogen Initiative.

The Public Fuel Cell Alliance

The PFCA is a coalition of state and federal agencies working together to accelerate the development and deployment of fuel cell and hydrogen infrastructure development. It is the only nonprofit organization in the U.S. that coordinates public funding of fuel cells and hydrogen technologies at the state and regional level. The PFCA was officially organized by its members in 2003 as a project of the Clean Energy States Alliance (CESA). CESA is a fourteen-state consortium of clean energy funds dedicated to supporting renewable power technology development.

As with many other clean energy technologies, state-based initiatives are leading the way to commercialization of these technologies. In particular, many states have promulgated renewable portfolio standards (RPS), creating new opportunities for fuel cells and distributed generation. States are funding demonstration projects for hydrogen production from renewable energy sources and are leading efforts to promote hydrogen fuel cells in security applications, providing reliable power supplies to critical telecommunications and emergency infrastructure.

The founding members of the PFCA include:

Federal

DOD: US Army Corps of Engineers, Construction Engineering Research Laboratory
DOE: National Energy Technology Laboratory
Bonneville Power Association

State

CT: Connecticut Clean Energy Fund
DE: Delaware Economic Development Office
MA: Massachusetts Technology Collaborative Renewable Energy Trust
NJ: New Jersey BPU
OH: Ohio Fuel Cell Initiative
PA: Sustainable Development Fund and 3 PA-based community funds
RI: Renewable Energy Fund

Supporting Private

Fuel Cell Energy

PFCA's mission is to bring together and align state and federal programs with industry partners to accelerate the commercialization of fuel cell and hydrogen technologies. Current activities are designed to further the PFCA's objectives to:

- Foster increased public collaboration by expanding the existing network of state, federal and local funding agencies to more states and agencies;
- Encourage additional state and regional commitments of public funding streams and to create new public funding mechanisms for these technologies;
- Develop and support regional strategies in various parts of the country to accelerate technology adoption and economic development (particularly for impacted communities);
- Devise more effective programs to explore renewable sources of hydrogen production, homeland security applications and linkages between stationary power and transportation; and
- Engage leading academic strategists on new approaches to technology innovation and deployment in order to develop alternative energy sources and energy infrastructure.

The Upper Midwest Hydrogen Initiative

The Upper Midwest Hydrogen Initiative is a recently announced effort to develop up to twelve "energy stations" throughout the Northern Plains states (and potentially extending into Canada) that would demonstrate a range of hydrogen production systems. The program is in its initial startup and fund-raising stage. The initiative is seeking partners to develop a network of hydrogen stations approximately every 150 miles along a network in Iowa, Michigan, Minnesota, South Dakota, North Dakota, Wisconsin, and the Canadian province of Manitoba. The project hopes to complete the first three stations by 2007 and the full network of twelve stations by 2012 (Great Plains Institute, 2006).

The specific projects mentioned include:

- ethanol-to-hydrogen using onsite ethanol reforming;
- wind-to-hydrogen using electrolysis;
- methane-to-hydrogen using anaerobic digestion of organic wastes;
- coal-to-hydrogen with carbon sequestration at the Dakota gasification facility in Beulah, North Dakota;

- byproduct hydrogen from an industrial process; and
- ammonia-to-hydrogen.

The effort makes specific reference to developing hydrogen energy stations that include electricity production as well as hydrogen for vehicles, and that also potentially use waste heat for cogeneration or "combined heat and power" (Great Plains Institute, 2006).

Appendix B: Summary Tables of "Plant-Gate"and Delivered Hydrogen Costs

Table B-1: Summary of Recent Hydrogen Production (or "Plant Gate") Cost Estimates

Production Method	Scale of Production	Production Cost (HHV basis)	Key Details and Market Status	Source
Natural Gas				
Steam Methane Reforming	239 kg/day 884 kg/day 2,390 kg/day *Small-Medium*	\$5.39/kg (\$37.96/GJ) \$2.76/kg (\$19.44/GJ) \$1.92/kg (\$13.52/GJ)	*Near Term*	Ogden et al., 1996
Steam Methane Reforming	625 kg/day *Small*	\$2.60/kg (\$18.31/GJ) Single station \$1.93/kg (\$13.59/GJ) 100 stations \$1.68/kg (\$11.83/GJ) 10,000 stations	NG at \$6.16/GJ "Energy station" with 100 kW of power sold to grid *Near Term*	Thomas et al., 2001
Steam Methane Reforming	609,000 kg/day (1 GW_{H2}) *Large*	\$0.78/kg (\$5.50/GJ) (NG@\$3.00/GJ) \$0.94/kg (\$6.60/GJ) (NG@\$3.90/GJ) \$0.97/kg (\$6.85/GJ) (NG@\$4.10/GJ)	NG at \$3.00-4.10/GJ 81% SMR efficiency *Commercial*	Williams, 2002
Steam Methane Reforming	609,000 kg/day (1 GW_{H2}) *Large*	\$1.02/kg (\$7.20/GJ)	NG at \$3/GJ 81% SMR efficiency 85% of CO_2 emissions captured *Research and Devt.*	Williams, 2002
Steam Methane Reforming	470 kg/day *Small*	\$4.40/kg (\$30.99/GJ)	NG at \$5.25/GJ Small-scale prod. *Near Term*	Simbeck and Chang, 2002
Steam Methane Reforming	609,000 kg/day (1 GW_{H2}) *Large*	\$0.90/kg (\$6.33/GJ)	NG at \$3.67/GJ CO_2 vented *Commercial*	Ogden et al., 2004
Steam Methane Reforming	609,000 kg/day (1 GW_{H2}) *Large*	\$1.14/kg (\$8.04/GJ)	NG at \$3.67/GJ 85% of CO_2 emissions captured *Research and Devt.*	Ogden et al., 2004
Steam Methane Reforming	480 kg/day *Small*	\$3.51/kg (\$24.75/GJ) Current \$2.33/kg (\$16.43/GJ) Future	NG at \$6.16/GJ SMR efficiency: 60% (current) 70% (future) *Near Term/Future*	NRC, 2004
Steam Methane Reforming	24,000 kg/day *Medium*	\$1.38/kg (\$9.73/GJ) Current \$1.21/kg (\$8.53/GJ) Future	NG at \$4.27/GJ SMR efficiency: 72% (current) 77% (future) *Near Term/Future*	NRC, 2004

Table B-1: Summary of Recent Hydrogen Production (or "Plant Gate") Cost Estimates (CONTINUED)

Production Method	Scale of Production	Production Cost (HHV basis)	Key Details and Market Status	Source
Natural Gas				
Steam Methane Reforming	24,000 kg/day *Medium*	\$1.76/kg (\$12.41/GJ) Current \$1.55/kg (\$10.93/GJ) Future	NG at \$4.27/GJ CO_2 sequestered SMR efficiency: 69% (current) 72% (future) *Near Term/Future*	NRC, 2004
Steam Methane Reforming	1.1 million kg/day *Large*	\$1.03/kg (\$7.26/GJ) Current \$0.92/kg (\$6.49/GJ) Future	NG at \$4.27/GJ SMR efficiency: 76.2% (current) 80% (future) *Near Term/Future*	NRC, 2004
Steam Methane Reforming	1.1 million kg/day *Large*	\$1.31/kg (\$9.24/GJ) Current \$1.10/kg (\$7.76/GJ) Future	NG at \$4.27/GJ CO_2 sequestered SMR efficiency: 72% (current) 78% (future) *Near Term/Future*	NRC, 2004
Natural Gas/Solar Assist				
Concentrating Solar NG Reactor	250 kg/day 450 kg/day 748 kg/day *Small*	\$2.56/kg (\$18/GJ) (8,750 m^2 heliostat) \$2.84/kg (\$20/GJ) (4.375 m^2 heliostat) \$3.41/kg (\$24/GJ) (2,188 m^2 heliostat)	NG at \$3.72/GJ *Research and Devt.*	Spath and Amos, 2002
Coal				
Oxygen-blown Gasification	313,090 kg/day *Large*	\$0.92/kg (\$6.48/GJ)	CO_2 vented 63.7% effic. (HHV) 20.4 MW net power *Commercial*	Gray and Tomlinson, 2002
Oxygen-blown Gasification	284,410 kg/day *Large*	\$1.10/kg (\$7.75/GJ)	CO_2 sequestered for \$10/ton of carbon 59.0% effic. (HHV) 26.9 MW net power *Research and Devt.*	Gray and Tomlinson, 2002
Advanced Gasification With Hot Gas Cleanup	377,620 kg/day *Large*	\$0.79/kg (\$5.56/GJ)	CO_2 sequestered for \$10/ton of carbon 75.5% effic. (HHV) 25.0 MW net power *Research and Devt.*	Gray and Tomlinson, 2002
Oxygen-blown Gasification	150,000 kg/day *Large*	1.62/kg (\$11.41/GJ)	Coal at \$29.11/ton CO_2 vented *Commercial*	Simbeck and Chang, 2002

Table B-1: Summary of Recent Hydrogen Production (or "Plant Gate") Cost Estimates (CONTINUED)

Production Method	Scale of Production	Production Cost (HHV basis)	Key Details and Market Status	Source
Coal				
Oxygen-blown Gasification	609,000 kg/day (1 GW_{H2}) *Large*	$0.89/kg ($6.25/GJ)	Coal at $1.17/GJ CO_2 vented *Commercial*	Williams, 2002
Oxygen-blown Gasification	1.2 million kg/day *Large*	$0.96/kg ($6.77/GJ) Current $0.71/kg ($5.01/GJ) Future	Coal at $1.16/GJ CO_2 vented *Commercial/Future*	NRC, 2004
Oxygen-blown Gasification	1.2 million kg/day *Large*	$1.19/kg ($8.39/GJ) Current $0.92/kg ($6.49/GJ) Future	Coal at $1.16/GJ CO_2 sequestered *Commercial/Future*	NRC, 2004
Oxygen-blown Gasification	609,000 kg/day (1 GW_{H2}) *Large*	$0.81/kg ($5.69/GJ)	CO_2 vented *Commercial*	Ogden et al., 2004
Oxygen-blown Gasification	609,000 kg/day (1 GW_{H2}) *Large*	$1.05/kg ($7.36/GJ)	CO_2 sequestered *Research and Devt.*	Ogden et al., 2004
Petroleum Coke				
Gasification	150,000 kg/day *Large*	$1.35/kg ($9.51/GJ)	CO_2 vented 21.0 MW net power *Near Commercial.*	Simbeck and Chang, 2002
Nuclear				
SI-MHR	n.s. *Large*	$0.95-1.60/kg ($6.69-11.28/GJ)	5-15% interest rate *Research and Development*	Brown et al., 2002
SI-MHR	n.s. *Large*	$1.30/kg ($9.15/GJ)	$686/kW cap. cost 10% interest rate *Research and Devt.*	Henderson, 2002
Nuclear Thermal of Water	1.2 million kg/day *Large*	$1.63/kg ($11.50/GJ) Future	$2.5 million plant capital cost *R&D/Future*	NRC, 2004

Table B-1: Summary of Recent Hydrogen Production (or "Plant Gate") Cost Estimates (CONTINUED)

Production Method	Scale of Production	Production Cost (HHV basis)	Key Details and Market Status	Source
Biomass				
Battelle Gasifier	147,900 kg/day *Large*	$0.84/kg ($5.9/GJ) ($2/GJ biomass, 6% DR) $1.21/kg ($8.5/GJ) (($4/GJ biomass, 6% DR) $0.97/kg ($6.8/GJ) (($2/GJ biomass, 12% DR) $1.33/kg ($9.4/GJ) (($4/GJ biomass, 12% DR)	Biomass at $2-4/GJ 70% thermal effic. *Demonstration*	Ogden and Nitsch, 1993
Pyrolysis	Not specified	$1.09/kg ($7.70/GJ)	Phenolic co-product sold for $0.44/kg *Commercial*	French et al., 2000
Battelle/FERCO Gasifier	22,737 kg/day *Medium*	$1.12/kg ($7.90/GJ) *$2.43/kg ($17.08/GJ) With 15% after tax IRR*	$54 mill. cap. Cost *Demonstration*	Spath et al, 2000
Battelle/FERCO Gasifier	75,790 kg/day *Medium*	$1.25/kg ($8.81/GJ) *$2.19/kg ($15.39/GJ) With 15% after tax IRR*	$129 mill. cap. Cost *Demonstration*	Spath et al, 2000
Battelle/FERCO Gasifier	113,685 kg/day *Large*	$1.19/kg ($8.41/GJ) *$2.03/kg ($14.29/GJ) With 15% after tax IRR*	$172 mill. cap. Cost *Demonstration*	Spath et al, 2000
IGT Gasifier	22,737 kg/day *Medium*	$1.19/kg ($8.40/GJ) *$2.93/kg ($20.64/GJ) With 15% after tax IRR*	$72 mill. cap. cost *Demonstration*	Spath et al, 2000
IGT Gasifier	75,790 kg/day *Medium*	$1.27/kg ($8.95/GJ) *$2.50/kg ($17.61/GJ) With 15% after tax IRR*	$169 mill. cap. cost *Demonstration*	Spath et al, 2000
IGT Gasifier	113,685 kg/day *Large*	$1.20/kg ($8.48/GJ) *$2.29/kg ($16.16/GJ) With 15% after tax IRR*	$227 mill. cap. cost *Demonstration*	Spath et al, 2000
Pyrolysis	22,737 kg/day *Medium*	$0.93/kg ($6.57/GJ) *$1.45/kg ($10.24/GJ) With 15% after tax IRR*	$19 mill. cap. cost *Commercial*	Spath et al, 2000

Table B-1: **Summary of Recent Hydrogen Production (or "Plant Gate") Cost Estimates** (CONTINUED)

Production Method	Scale of Production	Production Cost (HHV basis)	Key Details and Market Status	Source
Biomass				
Pyrolysis	75,790 kg/day *Medium*	$0.75/kg ($5.30/GJ) *$1.23/kg ($8.69/GJ) With 15% after tax IRR*	$59 mill. cap cost *Commercial*	Spath et al, 2000
Gasifier	24,000 kg/day *Medium*	$4.63/kg ($32.65/GJ) Current $2.21/kg ($15.59/GJ) Future	Biomass at: $2.85/GJ (current) $1.91/GJ (future) CO_2 vented *Near Term/Future*	NRC, 2004
Gasifier	24,000 kg/day *Medium*	$5.08/kg ($35.83/GJ) Current $2.53/kg ($17.84/GJ) Future	Biomass at: $2.85/GJ (current) $1.91/GJ (future) CO_2 sequestered *Near Term/Future*	NRC, 2004
Wind				
Electrolysis	1,267 kg/day *Small-Medium*	$1.56/kg ($11.0/GJ) (6% DR) $2.27/kg ($16.0/GJ) (12% DR)	Excellent sites (630 W/m^2) *Near Commercial*	Ogden and Nitsch, 1993
Electrolysis	1,267 kg/day *Small-Medium*	$2.41/kg ($17.0/GJ) (6% DR) $3.55/kg ($25.0/GJ) (12% DR)	Good sites (350 W/m^2) *Near Commercial*	Ogden and Nitsch, 1993
Electrolysis	n.s. 10 MW of wind power *Small-Medium*	$3.90/kg ($27.5/GJ) Year 2000 $3.00/kg ($21.1/GJ) Year 2010	Grid-Tied Wind power: $900/kW (2000) $700/kW (2010)	Mann et al., 1998
Electrolysis	n.s. 10 MW of wind power *Small-Medium*	$7.10/kg ($50.0/GJ) Year 2000 $4.00/kg ($28.2/GJ) Year 2010	Stand-Alone Wind power: $900/kW (2000) $700/kW (2010)	Mann et al., 1998
Electrolysis	n.s. *Small-Medium*	$1.86-2.63/kg ($13.00-18.50/GJ) *$3.20-3.98/kg ($22.50-28.00/GJ) w/15% IRR, 37% taxation*	Grid-Tied Various Design and Econ. Assumption	Padro, 2002
Electrolysis	n.s. *Small*	$1.14/kg ($8.00/GJ) *$4.33/kg ($30.50/GJ) w/15% IRR, 37% taxation*	Stand-Alone	Padro, 2002

Table B-1: **Summary of Recent Hydrogen Production (or "Plant Gate") Cost Estimates** (CONTINUED)

Production Method	Scale of Production	Production Cost (HHV basis)	Key Details and Market Status	Source
Wind				
Electrolysis	1,600 kg/day Current 1,200 kg/day Future *Small-Medium*	$10.69/kg ($75.39/GJ) Current $2.86/kg ($20.17/GJ) Future	Stand-Alone *Near Term/Future*	NRC, 2004
Electrolysis	480 kg/day *Small*	$6.81/kg ($48.03/GJ) Current $3.50/kg ($24.68/GJ) Future	Grid-Tied *Near Term/Future*	NRC, 2004
Solar				
PV Electrolysis	1,267 kg/day *Small-Medium*	$6.39-14.34/kg ($45-101/GJ) (6% DR) *$10.37-23.71/kg* *($73-167/GJ)* *(12% DR)*	ca. 1991 Southwest U.S. *Near Commercial*	Ogden and Nitsch, 1993
PV Electrolysis	1,267 kg/day *Small-Medium*	$1.42-2.27/kg ($10-16/GJ) (6% DR) *$2.13-3.55/kg* *($15-25/GJ)* *(12% DR)*	Future Projection Southwest U.S. *Near Commercial*	Ogden and Nitsch, 1993
PV Electrolysis	10 MWe *Small-Medium*	$25.84/kg ($182/GJ) $12.21/kg ($86/GJ) $6.39/kg ($45/GJ)	PV at $5,000/kW PV at $2,000/kW PV at $750/kW *Near Commercial*	Glatzmaier et al., 1998
Solar Dish-Stirling Electrolysis	10 MWe *Small-Medium*	$11.64/kg ($82/GJ) $10.79/kg ($76/GJ)	Year 2010 Year 2020 *Demonstration*	Glatzmaier et al., 1998
Solar Power-Tower Electrolysis	200 MWe *Medium*	$7.10/kg ($50/GJ) $5.96/kg ($42/GJ)	Year 2010 Year 2020 *Demonstration*	Glatzmaier et al., 1998
High-Temperature Electrolysis	200 MWe *Medium*	$5.68-6.25/kg ($40-44/GJ) $7.67-11.42/kg ($54-79/GJ)	$500/kW electrolyzer $2,000/kW electrolyzer *Research and Devt.*	Glatzmaier et al., 1998
PV Electrolysis	n.s. 10 MW of solar power *Small-Medium*	$7.40/kg ($52.1/GJ) Year 2000 $4.50/kg ($37.1/GJ) Year 2010	Grid-Tied Solar power: $3,133/kW (2000) $12,662/kW (2010) *Near Term/Future*	Mann et al., 1998

Table B-1: Summary of Recent Hydrogen Production (or "Plant Gate") Cost Estimates (CONTINUED)

Production Method	Scale of Production	Production Cost (HHV basis)	Key Details and Market Status	Source
Solar				
PV Electrolysis	n.s. 10 MW of solar power *Small-Medium*	$17.60/kg ($124.0/GJ) Year 2000 $7.50/kg ($52.8/GJ) Year 2010	Stand-Alone Solar power: $3,133/kW (2000) $12,662/kW (2010) *Near Term/Future*	Mann et al., 1998
PV Electrolysis	n.s. *Small-Medium*	$2.13-2.91/kg ($15.00-20.50/GJ) *$4.83-5.54/kg ($34.00-39.00/GJ) w/15% IRR, 37% taxation*	Grid-Tied Various Design and Econ. Assumption *Future*	Padro, 2002
PV Electrolysis	n.s. *Small*	$1.78/kg ($12.50/GJ) *$8.24/kg ($58.00/GJ) w/15% IRR, 37% taxation*	Stand Alone *Future*	Padro, 2002
PV Electrolysis	2,400 kg/day *Small-Medium*	$28.19/kg ($198.81/GJ) Current $6.18/kg ($43.58/GJ) Future	Stand-Alone *Near Term/Future*	NRC, 2004
PV Electrolysis	480 kg/day *Small*	$9.71/kg ($68.48/GJ) Current $4.37/kg ($30.82/GJ) Future	Grid-Tied *Near Term/Future*	NRC, 2004
Grid Power				
Electrolysis	24,000 kg/day *Medium*	$4.70/kg ($33.15/GJ) Current $2.30/kg ($16.22/GJ) Future	Electricity at $0.045/kWh *Near Term/Future*	NRC, 2004
Electrolysis	480 kg/day *Small*	$6.58/kg ($46.41/GJ) Current $3.93/kg ($27.72/GJ) Future	Electricity at $0.07/kWh *Near Term/Future*	NRC, 2004
Solar Photo-Electrochemical				
PEC Water Splitting	n.s. *Variable*	$2.60/kg ($17.50/GJ) *$11.00/kg ($77.50/GJ) w/15% IRR, 37% taxation*	Year 2010 Estimate *Research and Devt.*	Padro, 2002

Table B-1: Summary of Recent Hydrogen Production (or "Plant Gate") Cost Estimates (CONTINUED)

Production Method	Scale of Production	Production Cost (HHV basis)	Key Details and Market Status	Source
Solar Photo-Electrochemical				
PEC Water Splitting	n.s. *Variable*	$1.21/kg ($8.50/GJ) *$5.11/kg ($36.00/GJ) w/15% IRR, 37% taxation*	Year 2020 Estimate *Research and Devt.*	Padro, 2002

Notes: Production costs are on HHV basis unless otherwise specified. For delivered hydrogen cost estimates, see Table A-2. DR = discount rate (see list of acronyms at front of report for other abbreviations).

Table B-2: Summary of Recent Delivered Hydrogen Cost Estimates

Production Method	Scale of Production	Delivered H_2 Cost (HHV basis)	Notes	Source
Natural Gas				
Steam Methane Reforming	2,455 kg/day (2.7 tons/day)	$3.57/kg ($25.14/GJ)\	Distributed production	Moore and Raman, 1998
Steam Methane Reforming	24,550 kg/day (27 tons/day)	$3.35/kg ($23.59/GJ)	Central production Liquid H_2 delivery	Moore and Raman, 1998
Steam Methane Reforming	24,550 kg/day (27 tons day)	$2.91/kg ($20.49/GJ)	Central production Pipeline H_2 delivery	Moore and Raman, 1998
Steam Methane Reforming	Conv. SMR Advanced SMR 2,390 kg/day	$1.92/kg ($13.54/GJ) $2.76/kg ($19.46/GJ)	Distributed production	Ogden et al., 1998
Steam Methane Reforming	High demand Low demand 239,000 kg/day	$1.49/kg ($10.51/GJ) $1.93/kg ($13.61/GJ)	Central production Pipeline delivery	Ogden et al., 1998
Steam Methane Reforming	470 kg/day	$4.40/kg ($30.99/GJ)	Distributed production High pressure storage	Simbeck and Chang, 2002
Steam Methane Reforming	150,000 kg/day	$3.66/kg ($25.77/GJ)	Central production Liquid H_2 delivery	Simbeck and Chang, 2002
Steam Methane Reforming	150,000 kg/day	$5.00/kg ($35.21/GJ)	Central production Pipeline delivery	Simbeck and Chang, 2002
Steam Methane Reforming	150,000 kg/day	$4.39/kg ($30.92/GJ)	Central production Tube trailer delivery	Simbeck and Chang, 2002
Steam Methane Reforming	480 kg/day	$3.51/kg ($24.75/GJ) *Current* $2.33/kg ($16.43/GJ) *Future*	Distributed production High pressure storage	NRC, 2004

Table B-2: Summary of Recent Delivered Hydrogen Cost Estimates (CONTINUED)

Production Method	Scale of Production	Delivered H_2 Cost (HHV basis)	Notes	Source
Natural Gas				
Steam Methane Reforming	24,000 kg/day	$3.81/kg ($26.87/GJ) *Current* $2.62/kg ($18.48/GJ) *Future*	Central production Tanker truck delivery (liquid H_2)	NRC, 2004
Steam Methane Reforming	24,000 kg/day	$4.18/kg ($29.48/GJ) *Current* $2.95/kg ($20.81/GJ) *Future*	Central production with CO_2 sequestered Tanker truck delivery (liquid H_2)	NRC, 2004
Steam Methane Reforming	1.1 million kg/day	$1.98/kg ($13.96/GJ) *Current* $1.61/kg ($11.35/GJ) *Future*	Central production Pipeline delivery	NRC, 2004
Steam Methane Reforming	1.2 million kg/day	$2.26/kg ($15.94/GJ) *Current* $1.80/kg ($12.69/GJ) *Future*	Central production with CO_2 sequestered Pipeline delivery	NRC, 2004
Coal				
Oxygen-blown Gasification	609,000 kg/day ($1\ GW_{H2}$)	$2.21/kg ($15.57/GJ)	Central production CO_2 vented	Ogden et al., 2004
Oxygen-blown Gasification	609,000 kg/day ($1\ GW_{H2}$)	$2.45/kg ($17.24/GJ)	Central production CO_2 sequestered	Ogden et al., 2004
Gasification	150,000 kg/day	$4.51/kg ($31.76/GJ)	Central production Liquid H_2 delivery	Simbeck and Chang, 2002
Gasification	150,000 kg/day	$5.62/kg ($39.58/GJ)	Central production Pipeline delivery	Simbeck and Chang, 2002
Gasification	150,000 kg/day	$5.18/kg ($36.48/GJ)	Central production Tube trailer delivery	Simbeck and Chang, 2002
Gasification	1.2 million kg/day	$1.91/kg ($13.47/GJ) *Current* $1.40/kg ($9.87/GJ) *Future*	Central production Pipeline delivery	NRC, 2004
Gasification	1.2 million kg/day	$2.15/kg ($15.16/GJ) *Current* $1.61/kg ($11.35/GJ) *Future*	Central production Pipeline delivery With CO_2 sequestered	NRC, 2004

Table B-2: Summary of Recent Delivered Hydrogen Cost Estimates (CONTINUED)

Production Method	Scale of Production	Delivered H_2 Cost (HHV basis)	Notes	Source
Petroleum Coke				
Gasification	150,000 kg/day	$5.35/kg ($37.68/GJ)	Central production Pipeline delivery	Simbeck and Chang, 2002
Nuclear				
Nuclear Thermal Conversion of Water	1.2 million kg/day	$2.33/kg ($16.43/GJ) *Future*	Central production Pipeline delivery	NRC, 2004
Wind				
Electrolysis	n.s. (10 MWp)	$3.17/kg ($22.3/GJ) *(6% DR)* $4.32/kg ($30.4/GJ) *(12% DR)*	Future projection Demonstration Scale	Ogden and Nitsch, 1993
Electrolysis	n.s. (750 MWp)	$3.42/kg ($24.1/GJ) *(6% DR)* $4.50/kg ($31.7/GJ) *(12% DR)*	Future projection City supply scale	Ogden and Nitsch, 1993
Electrolysis	1,600 kg/day Current 1,200 kg/day Future	$10.69/kg ($75.39/GJ) *Current* $2.86/kg ($20.17/GJ) *Future*	Distributed production Stand-Alone	NRC, 2004
Electrolysis	480 kg/day	$6.81/kg ($48.03/GJ) *Current* $3.50/kg ($24.68/GJ) *Future*	Distributed production Grid-Tied	NRC, 2004
Solar				
PV Electrolysis	n.s. (10 MWp)	$2.26-3.14/kg ($15.9-22.1/GJ) *(6% DR)* $3.12-4.59/kg ($22.0-32.3/GJ) *(12% DR)*	Future projection Southwest U.S. Demonstration Scale	Ogden and Nitsch, 1993
PV Electrolysis	n.s. (750 MWp)	$2.50-3.38/kg ($17.6-23.8/GJ) *(6% DR)* $3.32-4.77/kg ($23.4-33.6/GJ) *(12% DR)*	Future projection Southwest U.S. City supply scale	Ogden and Nitsch, 1993

Table B-2: Summary of Recent Delivered Hydrogen Cost Estimates (CONTINUED)

Production Method	Scale of Production	Delivered H_2 Cost (HHV basis)	Notes	Source
Solar				
PV Electrolysis	2,400 kg/day	$28.19/kg ($198.81/GJ) *Current* $6.18/kg ($43.58/GJ) *Future*	Distributed production Stand-Alone	NRC, 2004
PV Electrolysis	480 kg/day	$9.71/kg ($68.48/GJ) *Current* $4.37/kg ($30.82/GJ) *Future*	Distributed production Grid-Tied	NRC, 2004
Biomass				
Battelle/FERCO Gasifier	22,737 kg/day	$1.59/kg ($11.22/GJ) *$2.90/kg ($20.40/GJ)* *With 15% after tax IRR*	Central production Pipeline delivery (10 miles)[a]	Spath et al, 2000
Battelle/FERCO Gasifier	75,790 kg/day	$1.50/kg ($10.59/GJ) *$2.44/kg ($17.17/GJ)* *With 15% after tax IRR*	Central production Pipeline delivery (10 miles)[a]	Spath et al, 2000
Battelle/FERCO Gasifier	113,685 kg/day	$1.41/kg ($9.94/GJ) *$2.25/kg ($15.82/GJ)* *With 15% after tax IRR*	Central production Pipeline delivery (10 miles)[a]	Spath et al, 2000
IGT Gasifier	22,737 kg/day	$1.66/kg ($11.72/GJ) *$3.40/kg ($23.96/GJ)* *With 15% after tax IRR*	Central production Pipeline delivery (10 miles)[a]	Spath et al, 2000
IGT Gasifier	75,790 kg/day	$1.52/kg ($10.73/GJ) *$2.75/kg ($19.39/GJ)* *With 15% after tax IRR*	Central production Pipeline delivery (10 miles)[a]	Spath et al, 2000
IGT Gasifier	113,685 kg/day	$1.42/kg ($10.01/GJ) *$2.51/kg ($17.69/GJ)* *With 15% after tax IRR*	Central production Pipeline delivery (10 miles)[a]	Spath et al, 2000
Pyrolysis	22,737 kg/day	$1.40/kg ($9.89/GJ) *$1.93/kg ($13.56/GJ)* *With 15% after tax IRR*	Central production Pipeline delivery (10 miles)[a]	Spath et al, 2000
Pyrolysis	75,790 kg/day	$1.01/kg ($7.08/GJ) *$1.49/kg ($10.47/GJ)* *With 15% after tax IRR*	Central production Pipeline delivery (10 miles)[a]	Spath et al, 2000
Gasification	150,000 kg/day	$4.98/kg ($35.07/GJ)	Central production Liquid H_2 delivery	Simbeck and Chang, 2002
Gasification	150,000 kg/day	$6.29/kg ($44.30/GJ)	Central production Pipeline delivery	Simbeck and Chang, 2002

Table B-2: Summary of Recent Delivered Hydrogen Cost Estimates (CONTINUED)

Production Method	Scale of Production	Delivered H_2 Cost (HHV basis)	Notes	Source
Biomass				
Gasification	150,000 kg/day	\$5.77/kg (\$40.63/GJ)	Central production Tube trailer delivery	Simbeck and Chang, 2002
Gasification	24,000 kg/day	\$7.04/kg (\$49.65/GJ) *Current* \$3.62/kg (\$25.53/GJ) *Future*	Central production Tanker truck delivery (liquid H_2)	NRC, 2004
Gasification	24,000 kg/day	\$7.50/kg (\$52.89/GJ) *Current* \$3.89/kg (\$27.43/GJ) *Future*	Central production Tanker truck delivery (liquid H_2) CO_2 sequestered	NRC, 2004
Grid Power				
Electrolysis	480 kg/day	\$6.58/kg (\$46.41/GJ) *Current* \$3.93/kg (\$27.72/GJ) *Future*	Distributed production	NRC, 2004
Electrolysis	24,000 kg/day	\$7.12/kg (\$50.21/GJ) *Current* \$3.71/kg (\$26.17/GJ) *Future*	Central production Tanker truck delivery (liquid H_2)	NRC, 2004

Note: Delivered hydrogen costs are on HHV basis unless otherwise specified.

[a] See report for additional storage and transport methods, including 100-mile pipeline, 1,000-mile pipeline, onsite consumption, and “gas station” delivery.

Clean Energy Group (CEG) is a nonprofit organization established in January 1998 to increase the use of cleaner energy technologies in the U.S. and abroad through creative financing, business partnerships, public policy and advocacy.

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CleanEnergyGroup
Innovation in Finance, Technology & Policy

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