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Solar and Wind Technologies For Hydrogen Production

Report to Congress

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DEPARTMENT OF ENERGY
UNITED STATES OF AMERICA

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Preface

This Department of Energy (DOE) report is in response to section 812(e) of the Energy Policy Act of 2005. It is a detailed summary of the technology roadmaps[1] for solar- and wind-based hydrogen production. Included are descriptions of the Department's progress in establishing programs required by section 812, and recommendations for promoting solar- and wind-based hydrogen production technologies.

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[1] For the purposes of this report the term “roadmap” refers to documents that identify the critical technology targets and research focus areas necessary to overcome the barriers to making solar- and wind-based hydrogen production commercially competitive.

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1.0 Introduction

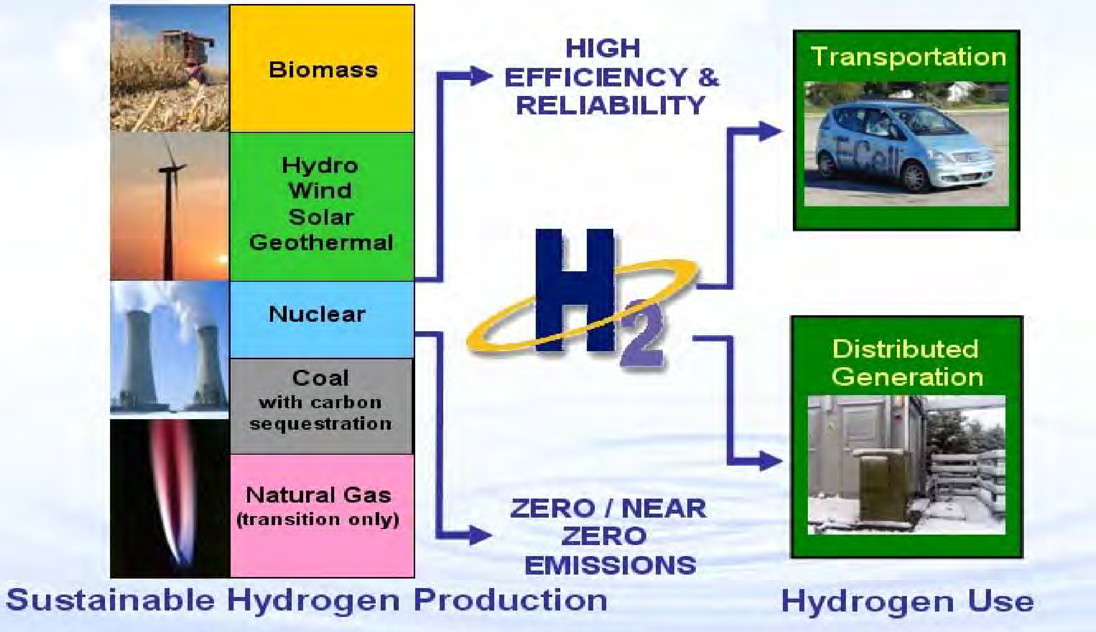
This Department of Energy (DOE) report is in response to section 812(e) of the Energy Policy Act of 2005. It is a detailed summary of the technology roadmaps[1] for solar- and wind-based hydrogen production. Included are descriptions of DOE's progress in establishing programs required by section 812, and recommendations for promoting solar- and wind-based hydrogen production technologies. This report also includes a comprehensive summary of DOE solar and wind hydrogen projects in the Appendix.

Hydrogen used as an energy carrier potentially offers the nation tremendous long-term energy, environmental, and economic security. Deriving hydrogen from domestic, carbon-neutral resources addresses foreign oil dependence, and criteria and greenhouse gas emissions.

In his 2003 State of the Union Address, President Bush announced a $1.2 billion Hydrogen Fuel Initiative[2] to reverse America's growing dependence on foreign oil and to improve the environment. Led by DOE, the Hydrogen Fuel Initiative seeks to develop hydrogen, fuel cell, and infrastructure technologies by 2015 so that industry can make it practical and cost-effective for Americans to choose hydrogen-powered fuel cell vehicles by 2020. On August 8, 2005, President Bush signed into law the Energy Policy Act of 2005 (Public Law 109-58). Title VIII of the Energy Policy Act of 2005, *Hydrogen*, strengthens and reinforces the President’s vision of a hydrogen economy.

DOE’s long-term strategy is to produce hydrogen from various resources: renewables (including solar, wind, biomass, hydropower, and geothermal), nuclear energy, and domestic coal (with sequestration of greenhouse gases). High efficiency and low emissions are achieved through use of fuel cells in both transportation and distributed electric power generation.

Figure 1.0: Hydrogen (H_2) – Clean, Efficient Energy from Diverse Domestic Resources



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[2] Office of the President, Press Release (January 30, 2003), *Hydrogen Fuel: A Clean and Secure Energy Future*, retrieved September 9, 2005, from www.whitehouse.gov/news/releases/2003/01/2003013020.html.

In February 2004, the National Academies' National Research Council released its report, *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs*, summarizing their findings and recommendations on hydrogen research planning. This important evaluation was requested by DOE in the fall of 2002, and will help guide the Hydrogen Program in the years ahead. The National Research Council Committee on Alternatives and Strategies for Future Hydrogen Production and Use, which produced the report, includes well-respected individuals with backgrounds in industry, academia, and government.

A basic conclusion from the National Academies' hydrogen report[3] was:

> *"A transition to hydrogen as a major fuel in the next 50 years could fundamentally transform the U.S. energy system, creating opportunities to increase energy security through the use of a variety of domestic energy sources for hydrogen production while reducing environmental impacts, including atmospheric* CO_2 *emissions and criteria pollutants."*

In this report the committee also recommended that DOE increase emphasis on carbon-dioxide-free production technologies.[4] The committee recommended increased emphasis on the development of wind-energy-to-hydrogen as an important technology for the hydrogen transition period and potentially for the longer term. The committee also recommended increased exploratory and fundamental research on hydrogen production by photoelectrochemical, photobiological, thin-film solar, and nuclear heat processes.

In August 2005, the National Research Council completed a review of the FreedomCAR and Fuel Partnership, and issued a press release stating, "A public-private effort to develop more fuel-efficient automobiles and eventually introduce hydrogen as a transportation fuel is well-planned and identifies all major hurdles the program will face."[5]

1.1 Options for Producing Hydrogen with Solar and Wind Energy

There are several options for producing hydrogen from renewable resources. These are listed in Table 1.1, below. Solar and wind energy are two technologies that are commercially available to provide electricity for electrolysis. The cost of electricity is a significant portion of the cost of making hydrogen with electrolysis. The production of hydrogen through electrolysis from solar and wind energy is not currently cost-competitive because of high electricity cost (relative to grid electricity at today's bulk electricity prices) and because electrolyzers require further development. Solar photovoltaic (PV) technology will be attractive as a potential source of electricity if the target price of electricity (5-7 ¢/kWh) for utility applications is achieved.[6] Wind energy is becoming attractive as a potential source of electricity for hydrogen production because of its cost, 3-5 ¢/kWh at sites with good wind speeds (15 mph at 10 meters), but is not competitive because of its intermittency.[7] In some instances it is already the least expensive source of new electricity capacity available. With sufficient electrical transmission capacity, and lower capital costs for electrolyzers, hydrogen's competitiveness with gasoline will improve.

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[3] *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs*, Committee on Alternatives and Strategies for Future Hydrogen Production and Use, National Research Council and National Academy of Engineering, 2004, p. 1.

[4] Ibid, p. 2.

[5] NRC Press Release, August 2, 2005, For the release of *Review of the Research Program of the FreedomCAR and Fuel Partnership*, Committee on Review of the FreedomCAR and Fuel Research Program, National Research Council and National Academies, 2005.

[6] *Solar Energy Technologies Program Multi-Year Technical Plan 2003-2007 and beyond,* DOE Office of Energy Efficiency and Renewable Energy, January 2004.

[7] *Wind Energy Multi-Year Program Plan for 2005-2010*, DOE Office of Energy Efficiency and Renewable Energy, November 2004.

Table 1.1: Options to Produce Hydrogen from Solar and Wind Resources

Options	Distributed Hydrogen Production	Centralized Hydrogen Production
Solar photovoltaic-based electrolysis	✓	✓
Wind-based electrolysis	✓	✓
Solar photoelectrochemical	✓	✓
Solar photobiological		✓
Solar thermochemical		✓

Different development models for near- and long-term hydrogen production and delivery to supply fuel for transportation range between distributed hydrogen production at fueling stations, and centralized hydrogen production to supply fuel to many stations. The distributed model requires electricity at each station for electrolysis, where an electrolyzer making 1500 kg of hydrogen per day could produce enough hydrogen to refuel 300 cars each day.[8] This electricity is generally assumed to be delivered via the electric transmission and distribution grid, but it can also be generated on site by solar or wind equipment. The advantages of on-site electricity generation include reduced electrical distribution requirements and system efficiency improvements. However, opportunities for on-site electricity generation are limited by resource availability and land-use restrictions. The advantage of distributed hydrogen production is that it avoids the large investment required to install a hydrogen delivery infrastructure by using existing or upgraded electrical transmission. Therefore, the distributed strategy is a possible option for transitioning to a hydrogen economy when market penetration is relatively small and doesn't justify large infrastructure investments. A possible variation of the distributed model is location of larger electrolyzers at production sites serving urban centers but separate from fueling stations, such sites near electrical substations, and delivering hydrogen to refueling stations via a local pipeline network or tube trailers. Benefits of this approach relative to production at fueling stations may include lower production costs from larger electrolyzers, improved ability to coordinate and optimize operations with electric service providers, and avoiding need for large electrical distribution service capacity upgrades and electrolyzer siting at fueling stations having limited space.

The centralized pathways will rely on a well-developed infrastructure (such as pipelines) to deliver the hydrogen to the points of use. The high costs and poor energy efficiency of near-term delivery methods (such as tube trailers and truck transport of liquid hydrogen) diminish the energy and environmental benefits of centralized hydrogen production. In the solar photovoltaic and wind electrolysis cases, the decision to build a central electrolyzer facility will depend on electrical grid capacity and cost, the ability to coproduce electricity or buy grid electricity, hydrogen delivery distance, hydrogen delivery infrastructure availability and cost, resource availability, electrolysis capacity factors, storage costs, and opportunities to reduce cost and efficiency losses with shared PV/wind and electrolyzer components.

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[8] DOE H2A Analysis, Exhibit 3, www.hydrogen.energy.gov/h2a_analysis.html.

The solar thermochemical, photoelectrochemical, and photobiological production options would avoid large electrolyzer units and produce hydrogen directly. As discussed later, research on solar-driven thermochemical cycles could be complete by 2015, while photoelectrochemical and photobiological technologies are in a relatively early stage of development, but show promise for low-cost, efficient hydrogen production in the long term.

1.2 Solar and Wind Energy Electrolysis Systems Integration

While the Nation's solar and wind resources offer a major opportunity for supplying energy for electricity and hydrogen production, their variability and intermittency can raise challenges for their integration into energy production and delivery systems at minimum cost, while ensuring high system reliability. Analyses of experience to date with integration of wind energy show modest additional costs for reliably operating systems with up to10% of electricity from wind, and in one country - Denmark - about 20% of electricity needs are currently met from wind.[9] Increasing levels of penetration of variable renewable energy sources can be aided by increased options for system operators to coordinate system loads with generation sources, and with forms of energy storage in the system. Hydrogen production through electrolysis may provide an opportunity to serve these purposes as a controllable load that produces a storable energy product, and thus could contribute to increasing the levels of variable renewable energy resources that can be harnessed.

DOE is engaging the electric utility and electrolysis industries to explore issues associated with providing electricity and designing systems to support widespread deployment of electrolysis-based hydrogen production in the United States. An Electrolysis-Utility Integration Workshop[10] was convened in September 2004, and discussion of the issues continues in forums, including in the solar and wind communities.[11]

Examples of workshops held with industry:

- Electrolysis Production of Hydrogen from Wind and Hydropower Workshop — September 9-10, 2003.
- Electrolysis-Utility Integration Workshop — September 22-23, 2004.
- Solar Hydrogen Workshop — November 9-10, 2004.

System integration issues for both centralized and distributed hydrogen production revolve around individual component costs and efficiencies. The capacity factors of wind and solar technologies drive the optimization of systems as well as contributions to greenhouse gas reduction. DOE has begun the process of establishing an electrolysis test facility at the National Renewable Energy Laboratory to explore system integration issues and the optimization of system configurations.

When considering renewable hydrogen production via electrolysis, system optimization is a key component. The balance of costs and efficiencies must be considered to determine the most economic scenario for any given location. Items such as resource availability, capacity factor,

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[9] Parsons, B.; Milligan, M.; Zavadil, B.; Brooks, D.; Kirby, B.; Dragoon, K.; Caldwell, J. (2004). *Grid Impacts of Wind Power: A Summary of Recent Studies in the United States*. Wind Energy. Vol. 7(2), 2004; pp. 87-108; NREL Report No. JA-500-38420.

[10] Workshop on Electrolysis-Utility Integration Proceedings, September 22-23, 2004. Posted at www.eere.energy.gov/hydrogenandfuelcells/wkshp_electrolysis.html.

[11] Workshop on Electrolysis Production of Hydrogen from Wind and Hydropower Proceedings, September 9-10, 2003. Posted at www.eere.energy.gov/hydrogenandfuelcells/wkshp_wind_hydro.html.

efficiency, generation options, and product options need to be considered. As a simple example, for central hydrogen electrolysis, the economics favor electricity coproduction.

1.3 Detailed Roadmaps for Solar and Wind Options for Hydrogen Production

Detailed roadmaps[1] have been developed and are being implemented to lower the costs of solar and wind technologies, one of the uses of which will be hydrogen production through electrolysis. These roadmaps address the requirements of sections 812(a)(1) and 812(b)(1) of the Energy Policy Act of 2005 and are summarized in this report. Each technology roadmap identifies technical and economic barriers, targets and milestones, technical approach, and a detailed multiyear schedule. These detailed roadmaps, listed in Table 1.3, were developed with input from industry, academia, and the national laboratories, and are referenced in the technology-specific sections of this report.

Table 1.3: Roadmaps for Solar- and Wind-Based Hydrogen Production

Technology and Roadmap Location	Technical Targets*	Barriers*	Milestones*
Hydrogen, fuel cells, and infrastructure	www.eere.energy.gov/hydrogenandfuelcells/mypp/		
Electrolysis	p. 3-12	pp. 3-19, 3-20	p. 3-32
Solar thermochemical hydrogen production	p. 3-18	p. 3-26	p. 3-34
Photoelectrochemical hydrogen production	p. 3-18	p. 3-25	p. 3-34
Photobiological hydrogen production	p. 3-16	p. 3-22	p. 3-32
Basic Energy Sciences report	www.sc.doe.gov/bes/reports/file/NHE_rpt.pdf		
Solar electricity	www.eere.energy.gov/solar/about.html		
Wind electricity	www.eere.energy.gov/windandhydro/		

* Page numbers refer to the roadmap indicated in the left column.

1.4 Potential Capacity for Hydrogen Production from Conventional Electrolysis Using Wind and Solar Energy

Hydrogen can be produced from solar and wind resources throughout the country. Figures 1.4a and 1.4b show the geographic distribution of the land-based energy resource potential to produce hydrogen via electrolysis from wind and solar energy sources. Wind resources in coastal waters have not been thoroughly assessed, but are estimated to be over 900 GW potential, and their proximity to coastal population centers make them potential resources for hydrogen and electricity production.[12]

Today, the U.S. light-duty vehicle fleet consists of 220 million automobiles and light trucks and consumes approximately 8 million barrels of petroleum per day and is expected to increase.[13] In 2040, roughly 64 million metric tons of hydrogen would be required annually to displace the petroleum used by the 300 million light duty vehicles projected to exist at that time.[14]

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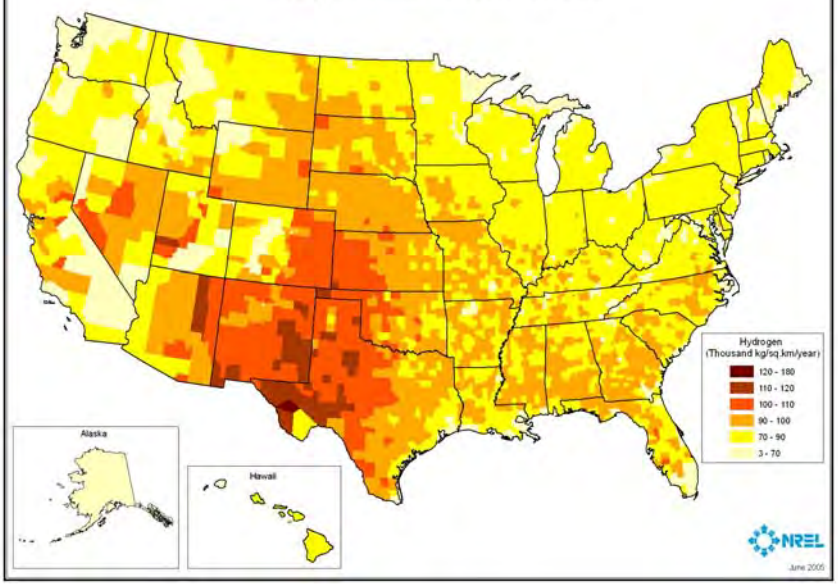
[12] *Wind Energy Program Multi-Year Program Plan 2005-2010*, DOE Office of Energy Efficiency and Renewable Energy, November 2004.

[13] Singh, M., et al., *Vision Model*, DOE, December 2003.

[14] U.S. Department of Energy Hydrogen Program, Record # 5008.

Data from the following resource maps indicate that the potential exists to use wind and solar resources to produce more than 15 times the amount of hydrogen needed to displace the petroleum used by light duty vehicles in 2040.[15] About one billion metric tons of hydrogen could be produced by renewable electrolysis annually, based upon solar and wind resource potential.[16] The other three solar pathways — thermochemical, photoelectrochemical, and photobiological — would have similar or possibly higher productivity per unit of land area. However, the infrastructure is not in place, and the majority of the solar and wind resources are located outside urban areas. The distribution and storage of hydrogen from point of generation to point of use will be key to economic, energy, and environmental impacts. Solar and wind energy could play an important role in our nation's hydrogen energy future, along with nuclear energy, coal with sequestration, biomass, and other renewables. All of these technologies require research and development to overcome technical and economic barriers to commercialization and economic production of hydrogen.

Figure 1.4a: Hydrogen Potential from Solar Resources[17]



Note: Map shows total kilograms of hydrogen per county, normalized by county area. Some environmental and land-use exclusions were applied in developing this map. Source: National Renewable Energy Laboratory.

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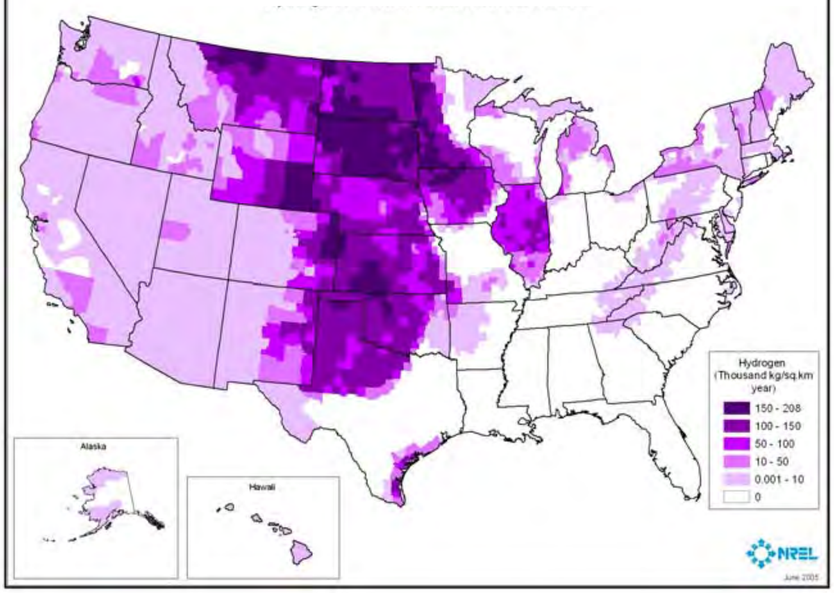
[15] U.S. Department of Energy Hydrogen Program, Record # 5011.
[16] Ibid.
[17] Ibid.

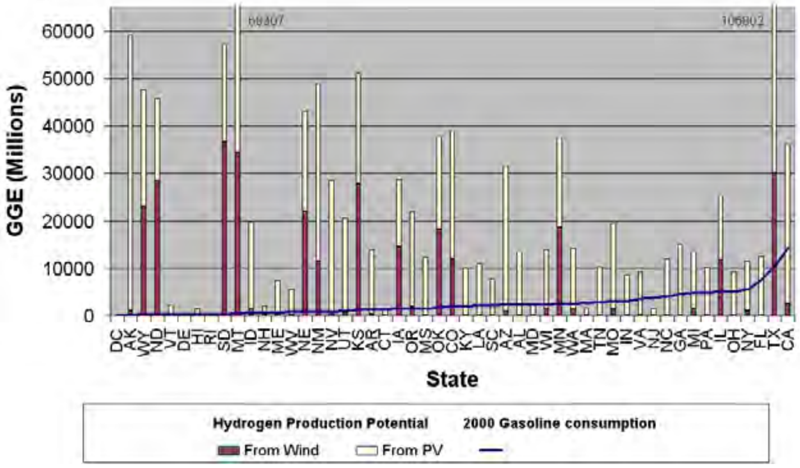
Figure 1.4b: Hydrogen Potential from Wind Resources[18]



Note: Map shows total kilograms of hydrogen per county, normalized by county area. Some environmental and land-use exclusions (e.g., wetlands, forests, national parks, and urban areas) were applied. Source: National Renewable Energy Laboratory.

Renewable hydrogen has the potential to replace gasoline consumption in most states. Figure 1.4c, below, identifies gasoline consumption in the year 2000 and the potential amount of hydrogen produced by electrolysis from solar and wind resources. The Energy Information Administration (EIA) reports that annual gasoline consumption in 2000 was 129 billion gallons, and 135 billion gallons in 2004, an increase of 4.6%.[19]

Figure 1.4c: Gasoline Use and Renewable Hydrogen Potential[20]



Note: The y-axis units of GGE stand for Gallons of Gasoline Equivalent and are equal to a gallon of gasoline or a kilogram of hydrogen. Gasoline consumption is plotted by the solid line in terms of gallons of gasoline consumed in the year 2000. The potential for hydrogen production is plotted in the dark bars (wind potential) and the light bars (PV potential).

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[18] U.S. Department of Energy Hydrogen Program, Record # 5011.

[19] Levene, J., et al., "An Analysis of Hydrogen Production from Renewable Electricity Sources." *ISES 2005 Solar World Congress: Proceedings of the 2005 Solar World Congress*, International Solar Energy Society, 2005.

[20] Ibid.

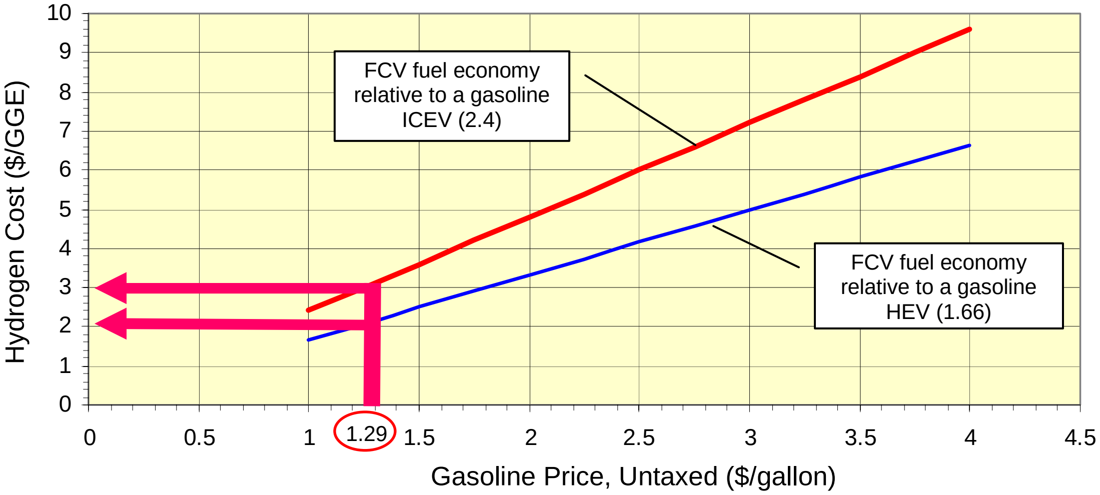
1.5 Cost-Competitive Hydrogen

The DOE Program goal is to have hydrogen fuel cost the same or less than gasoline on a cents per mile basis. The new hydrogen cost goal[21] of \$2.00-\$3.00/GGE (delivered, untaxed, in 2005\$, by 2015)[22] is independent of the pathway used to produce and deliver hydrogen. In addition, the new methodology accounts for the energy efficiency of improved gasoline-vehicle technologies and the fuel-cell vehicle on a cost-per-mile basis. The hydrogen target is in alignment with the Hydrogen Fuel Initiative goal of enabling an industry commercialization decision by 2015, and will be used to guide DOE's hydrogen and fuel cell research and development activities.

The competitive cost of hydrogen will depend on the gasoline vehicle technology in the market and the cost of petroleum. Figure 1.5, below, shows the hydrogen cost target for a fuel cell vehicle (FCV) compared to a gasoline internal combustion engine vehicle (ICEV) and to a gasoline hybrid electric vehicle (HEV).

Figure 1.5: Model for Hydrogen Cost Goal

(Equivalent \$/mile for consumer)



Note: FCVs are assumed to be 1.66 times more efficient than gasoline HEVs (*The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs*, Committee on Alternatives and Strategies for Future Hydrogen Production and Use, National Research Council and National Academy of Engineering, 2004, p. 66) and 2.4 times more efficient than gasoline ICEVs (Ibid, p. 26). EIA projected gasoline price of \$1.29 in 2015 is based on the high "A" case (*Annual Energy Outlook 2005*, Energy Information Administration, January 2005).

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[21] This is a research cost goal and not a hydrogen price.

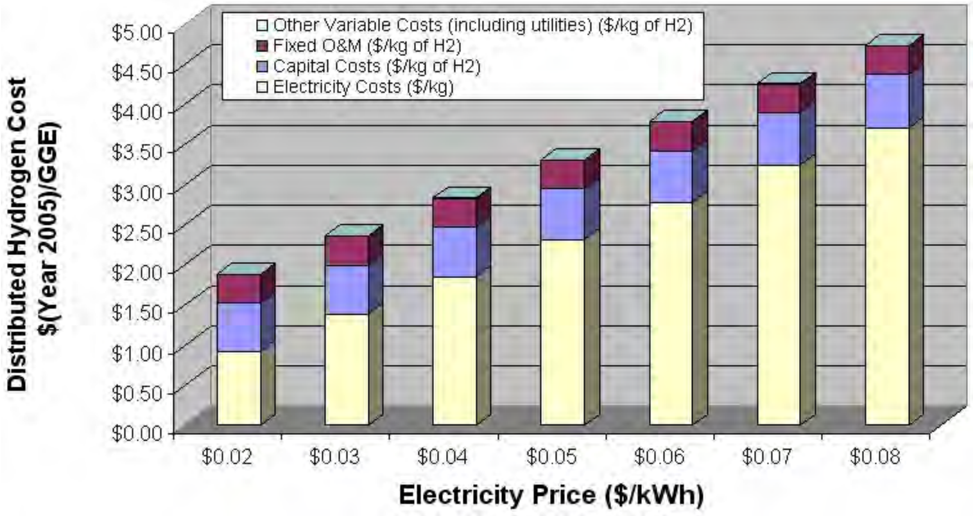
[22] U.S. Department of Energy Hydrogen Program, Record # 5013

1.6 Effect of Electricity Price on the Cost of Hydrogen Produced by Electrolysis

The price of electricity is a major component of the cost of hydrogen produced via electrolysis. As a consequence, integration with low-cost renewables such as wind energy, and the flexibility to produce hydrogen from grid electricity during off-peak periods, will be essential to producing hydrogen electrolytically at competitive prices.

Figure 1.6 depicts hydrogen production cost at electricity prices between 2 and 8 ¢/kWh, using the 2010 target for capital cost and efficiency for advanced electrolyzer technology (current state of technology is 56%-75% efficiency and $700/kW).[23]

Figure 1.6: Effect of Electricity Price on Distributed Hydrogen Production Cost[24]
(Assumes: 1500 GGE/day, electrolyzer at 76% efficiency, and capital cost of $250/kW)



The costs in Figure 1.6 represent hydrogen production at the forecourt and include compression, storage, and dispensing. The electrolyzer has a capacity factor of 70% to adjust for seasonal and weekend/weekday fluctuations in demand and a 97% availability of the equipment.[25] The figure does not represent any particular grid mix, as any combination of grid/solar/wind energy that meets the electricity price and electrical demands of the system could yield the resulting hydrogen costs.

1.7 Well-to-Wheels Energy Use and Greenhouse Gas Emissions

Producing hydrogen via electrolysis using wind and solar energy requires very little energy from petroleum-derived fuels. Using grid energy to increase the capacity factor of the electrolysis components does not substantially increase the quantity of petroleum consumed. Figure 1.7a depicts well-to-wheels energy use for several scenarios. Total energy use for distributed wind electrolysis technology with 50% grid assistance to the electrolyzer is 4600 Btu/mile; 34% of the total pathway energy, including compression and dispensing, is renewable. An independent

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[23] *Hydrogen, Fuel Cells & Infrastructure Technologies Program: Multi-Year Research, Development and Demonstration Plan - Planned program activities for 2003-2010*, DOE Office of Energy Efficiency and Renewable Energy, March 2005, p. 3-12.
[24] U.S. Department of Energy Hydrogen Program, Record #5014
[25] DOE H2A Analysis, Production Model Forecourt Hydrogen Production, www.hydrogen.energy.gov/h2a_analysis.html.

study[26] showed similar results of 4500 Btu/mile. This distributed future case is for the 2015 timeframe and assumes electrolyzer research is successful.

Figure 1.7a also depicts results for future central wind and solar electrolysis options, both with 50% of the electrolysis energy coming from the electrical grid. Total energy consumption of the central wind case is slightly higher than of the distributed case because of the energy used in hydrogen delivery. Lower electrical conversion efficiency increases the total energy use of the solar/grid electrolysis case, although 47% of the energy is renewable. These future cases are for the 2030 timeframe and assume a pipeline distribution infrastructure. If current delivery technology such as tube trailer or liquid hydrogen were assumed, the results would change significantly. Fuel cell vehicles running on hydrogen produced from water by wind and solar energy resources will use significantly less petroleum energy than gasoline-fueled vehicles. Critical assumptions are listed under Figure 1.7b. Once the technologies are mature and systems can be fully analyzed, it is expected that photoelectrochemical, photobiological, and thermochemical hydrogen production technologies would have similar low petroleum use and be competitive with improved conventional technologies on an overall energy use basis.

Figure 1.7a: Well-to-Wheels Energy Use[27]

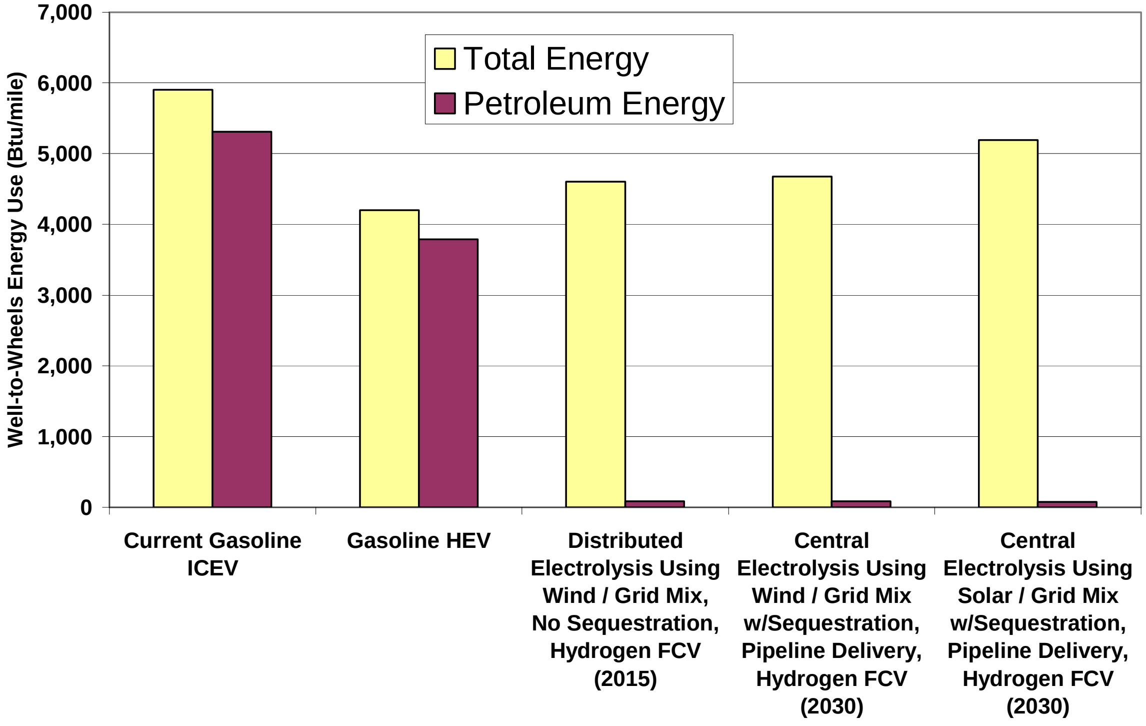

Figure 1.7b illustrates that fuel cell vehicles running on hydrogen produced from wind and solar energy resources will generate fewer greenhouse gas emissions than gasoline-fueled vehicles. When grid electricity is used to increase the capacity factor of the electrolysis components, as illustrated in the distributed wind/electrolysis case below, the majority of the greenhouse gas

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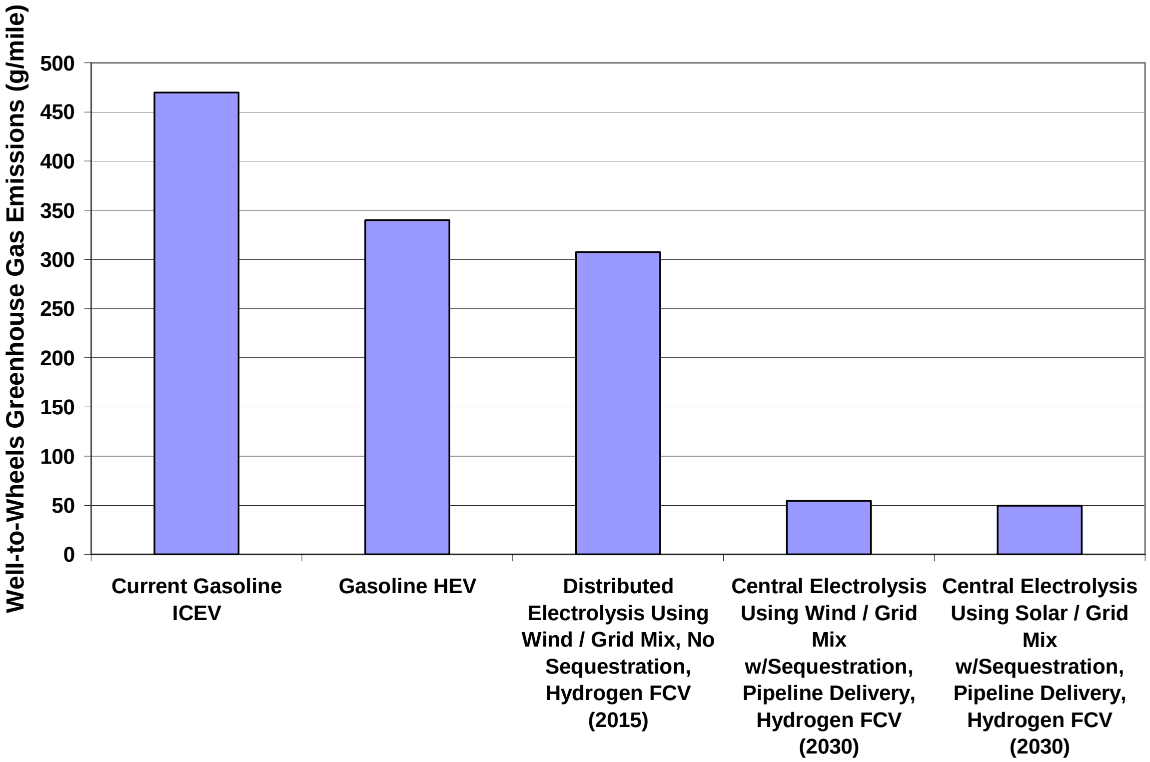
[26] U.S. Department of Energy Hydrogen Program, Record # 5012

[27] Ibid.

emissions are due to the fossil-based component of the electrical grid. Assuming a future scenario where fossil-fueled power plants on the grid are able to sequester 85% of their greenhouse gas emissions, as shown in the central cases below, greenhouse gas emissions are significantly reduced.[28] Again, the central case timeframe is 2030. Without such sequestration, the greenhouse gas emissions would still be below those from a gasoline-powered hybrid electric vehicle due to the higher efficiency of the vehicle. Greenhouse gas emissions from the central cases are also due to grid-powered pipeline delivery compression and compression at the fueling station. Once the technologies are mature and systems can be fully analyzed, it is expected that photoelectrochemical, photobiological, and thermochemical hydrogen production technologies would have similarly low greenhouse gas emissions.

Figure 1.7b: Well-to-Wheels Greenhouse Gas Emissions[29]



Note: Well-to-wheels petroleum use, renewable energy use, and greenhouse gas emissions calculated with the GREET model from Argonne National Laboratory. All hydrogen cases assume a 50%/50% mix of electricity from renewable/grid sources, with the grid assistance being used to increase the capacity factor on the electrolyzer components. Central Electrolysis Using Wind/Grid Mix and Central Electrolysis Using Solar/Grid Mix assume that 85% of the carbon produced by the grid is to be sequestered. For central cases, hydrogen delivery is by pipeline over 100 km, with pipeline energy supplied by the electrical grid with 85% carbon sequestration. For all cases, electrolyzer efficiency equals 44.5 kWh/kg hydrogen. For dispensing at fueling station, hydrogen is compressed to 6000 psi using grid energy, as defined by GREET. Fuel cell vehicle is as defined by GREET model. All cases assume that technology targets are achieved. All cases represent system configurations that have economic potential to compete with conventional gasoline and gasoline hybrid electric vehicle technology.[30]

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[28] U.S. Department of Energy Hydrogen Program, Record # 5012.

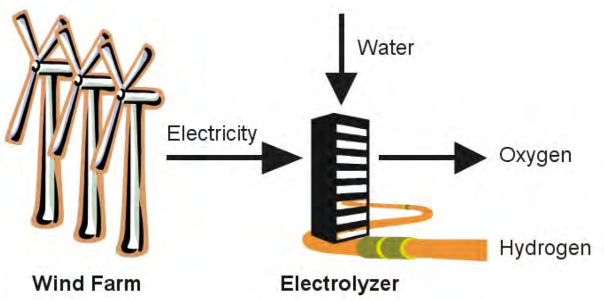
[29] Ibid.

[30] Ibid.

2.0 Electrolytic Hydrogen Production

Electrolysis is a process for breaking water (H_2O) into its constituent elements — hydrogen (H_2) and oxygen (O_2) — by supplying electrical energy. The advantage of this process is that it can produce a very clean hydrogen fuel that is free from carbon- and sulfur-based impurities, which can poison fuel cells. Distributed electrolysis may play a role in the transition to the hydrogen economy when the demand for hydrogen is small but growing and there is little delivery infrastructure for hydrogen.

Figure 2.0: Conceptual Diagram of Hydrogen Production from Wind Energy via Electrolysis



2.1 Electrolysis Technology Status

Electrolytic hydrogen production is an existing technology that serves a high-value industrial and chemical market. The keys to adapting this technology to meet energy-related applications in the future are reducing cost and enhancing performance.[31]

Alkaline is the most mature and is the current technology for most commercial systems in use today. Although PEM electrolysis systems are still higher cost, they are expected to mirror the cost reduction and improvements for fuel cells.

Today these electrolyzers have relatively high energy efficiencies themselves. The cost of hydrogen depends on the cost of electricity as well as the capital cost of the electrolyzer systems and their operating efficiency.

Table 2.1a: Range of Energy Efficiencies for Today's Electrolysis Systems[32]

Alkaline HHV* Efficiency (%)	PEM HHV* Efficiency (%)
57-75	56-70

* HHV is Higher Heating Value.

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[31] *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs*, Committee on Alternatives and Strategies for Future Hydrogen Production and Use, National Research Council and National Academy of Engineering, 2004, p. 99.

[32] Calculated from data in the following reports: *Summary of Electrolytic Hydrogen Production: Milestone Completion Report*, National Renewable Energy Laboratory, September 2004; and *2005 DOE Hydrogen Program Review: Low-Cost, High-Pressure Hydrogen Generator*, Giner Electrochemical Systems LLC, May 2005.

The current cost of distributed solar-based and wind-based hydrogen is approximately \$10 and \$7 per gallon gasoline equivalent.[33] One opportunity to reduce the cost of hydrogen produced by electrolysis is to replace part of the electricity requirement with heat, achieving higher overall energy efficiency. Concentrated solar energy and high temperature nuclear could supply sufficient heat to reduce the electrical requirement. Such systems are not in operation today, and would require solid oxide or other higher temperature electrolyzers.

The Hydrogen Program goal is to verify, by 2015, the preliminary feasibility of electrolysis to be competitive in the long term, by achieving the following technical targets for system energy efficiency and durability of distributed and central systems:

Table 2.1b: Technical Targets for Water Electrolysis[34]

			Distributed: 1500 kg/day refueling station		**Central Renewable**[a]
Characteristics		**Units**	**2003 Status**	**2010 Target**	**2015 Target**
Power conversion, cell stack, balance of plant	Cost	\$/GGE H_2	0.95	0.39	0.24
	Total cell efficiency	%	66	76	77
Compression, storage, dispensing	Cost	\$/GGE H_2	0.83	0.19	0.08
	Efficiency	%	94	99	99.5
Electricity	Cost	\$/GGE H_2	2.57	1.89	1.32
O&M	Cost	\$/GGE H_2	0.80	0.38	0.11
Total[b]	Cost	\$/GGE H_2	5.15	2.85	2.75[c]
	Efficiency	%	62	75	76

a Renewable option: Calculation based on delivering 50,000 GGE hydrogen per day (1000+ GGE/day modules) with the option of coproducing electricity. Electricity backup provided by existing electricity grid.

b Based on system capital cost per kW_e of \$700 and \$250 for the refueling station in 2003 and 2010, respectively, and \$200 for the central station in 2015. Assumes high volume annual production (1,000 units for all purposes and all markets) of electrolyzer units in 2010-2015 and centralized facility benefiting from scale on installation.

c Includes \$1.00/GGE delivery charge (transportation to the station, storing, and dispensing) for a national pipeline infrastructure.

The electricity costs in the table are at the EIA-projected industrial electricity rate for 2003. An electricity cost of \$0.04/kWh is assumed in 2010 based on the regional industrial electricity rate and the existence of new renewable technologies on the grid. The electricity cost of \$0.03/kWh assumed in 2015 is with central wind and grid assistance and corresponds to the Office of Wind and Hydropower's production cost goal for Class 4 wind resources.[35]

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[33] *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs*, Committee on Alternatives and Strategies for Future Hydrogen Production and Use, National Research Council and National Academy of Engineering, 2004, p. 52.

[34] *Hydrogen, Fuel Cells & Infrastructure Technologies Program: Multi-Year Research, Development and Demonstration Plan - Planned program activities for 2003-2010*, DOE Office of Energy Efficiency and Renewable Energy, March 2005, p. 3-12.

[35] *Wind Energy Multi-Year Program Plan for 2005-2010*, DOE Office of Energy Efficiency and Renewable Energy, November 2004.

The primary research challenge is to reduce the capital and operating costs of electrolysis systems. The current capital equipment cost for advanced electrolysis is between $600/kW and $700/kW. This cost needs to be reduced to $200/kW to achieve $2.75/GGE (untaxed) by 2015. The operating cost of an electrolyzer is driven by energy efficiency and the cost of electricity. Energy efficiency needs to be increased to 76% from the current average of about 62%.[36]

Basic research will provide underlying fundamental knowledge needed to provide improvements in electrolysis systems required to make this technology widely applicable. New classes of materials could be designed at the nanoscale to produce catalysts that are more selective, less prone to poisoning, and able to operate at lower temperatures. Similarly, new membranes can be designed on the nanoscale that improve operating parameters and also incorporate nanocatalysts in a single system, thereby reducing the complexity and improving future reliability of these devices.

2.2 Solar and Wind Energy Electrolysis Barriers

There are financial, technical, and environmental barriers facing the use of wind and solar energy to meet the DOE hydrogen targets. The cost of electricity from solar and wind technologies remains too high to achieve widespread deployment of solar- and wind-derived hydrogen. The current cost of PV technology ranges from 16 to 32 ¢/kWh depending on the market application.[37] While wind energy is the world's fastest growing energy technology, it still faces barriers of high initial capital investment, remote location of resources, and intermittency. Initial analysis results indicate the electricity costs will be a major price contributor to the price of hydrogen produced via electrolysis.[38]

Electrolyzers are typically designed to operate using grid-quality power (constant alternating current [AC] supply). Specialized power control and conditioning equipment needs to be developed to optimize the efficient integration of electrolyzers with wind and solar power sources, which are inherently intermittent and of variable quality.[39]

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[36] *Hydrogen, Fuel Cells & Infrastructure Technologies Program: Multi-Year Research, Development and Demonstration Plan - Planned program activities for 2003-2010*, DOE Office of Energy Efficiency and Renewable Energy, March 2005, p. 3-12.

[37] *Solar Energy Technologies Program Multi-Year Technical Plan 2003-2007 and beyond,* DOE Office of Energy Efficiency and Renewable Energy, January 2004.

[38] Levene, J., et al., "An Analysis of Hydrogen Production from Renewable Electricity Sources." *ISES 2005 Solar World Congress: Proceedings of the 2005 Solar World Congress*, International Solar Energy Society, 2005.

[39] *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs*, Committee on Alternatives and Strategies for Future Hydrogen Production and Use, National Research Council and National Academy of Engineering, 2004, Appendix G p. 221.

Technology development needs are as follows:

Table 2.2a: Electrolytic Hydrogen Production Barriers[40]

- **Capital Cost.** R&D is needed to develop lower cost materials with improved manufacturing capability to lower capital requirements while improving the efficiency and durability of the system.
- **System Efficiency.** New membrane, electrode, and system designs are needed. Mechanical high-pressure compression technology exhibits low energy efficiency and often reduces hydrogen purity while adding significantly to the system cost. Efficiency gains can be realized using electrochemical compression in the cell stack. Low-cost, high-pressure materials need to be developed to provide integral electrochemical or other high-pressure compression technologies to replace some or all mechanical compression stages. Development is need for low-cost cell stack optimization considering efficiency, electrochemical compression, and durability.
- **Grid Electricity Emissions.** Low-cost, carbon-free electricity sources are needed.
- **Renewable Integration.** Development of integrated renewable electrolysis systems is needed, including optimization of power conversion and other system components from renewable electricity to provide high-efficiency, low-cost integrated renewable hydrogen production. Novel concepts for carbon-free electrolytic hydrogen production need to be evaluated.
- **Electricity Costs.** High-temperature solid oxide electrolysis can use lower cost energy (in the form of steam) for water-splitting to decrease electricity consumption. Technically viable systems for low-cost manufacturing need to be developed for this technology. Electrolysis systems that can produce both hydrogen and electricity need to be evaluated. (Renewable electricity costs will be addressed by the DOE Office of Energy Efficiency and Renewable Energy (EERE) renewable power programs – Solar, Wind, Hydropower, Geothermal, and Biomass.)

2.3 Solar and Wind Energy Electrolysis Research Focus Areas

DOE is funding R&D to continue to reduce the costs of solar and wind technologies. The DOE Solar Program is currently pursuing the development of three generations of photovoltaic (PV) devices: discrete wafers of crystalline silicon, thin-film materials amenable to rapid manufacturing methods, and bandgap-engineered materials and novel quantum mechanical approaches (e.g., Periodic Table Group III-V materials, multijunctions, polymer cells, quantum-dot sensitized nanoparticle materials). The current cost of PV technology ranges from 16 to 32 ¢/kWh depending on the market application. The long range 2020 goals of the program are to achieve costs in the 8 to 10 ¢/kWh for residential systems, 6 to 8 ¢/kWh for commercial systems, and 5 to 7 ¢/kWh for utility applications. These values assume a grid-tied, battery-free, fully installed photovoltaic system.[41]

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[40] *Hydrogen, Fuel Cells & Infrastructure Technologies Program: Multi-Year Research, Development and Demonstration Plan - Planned program activities for 2003-2010*, DOE Office of Energy Efficiency and Renewable Energy, March 2005, pp. 3-19 and 3-20.

[41] *Solar Energy Technologies Program Multi-Year Technical Plan 2003-2007 and beyond,* DOE Office of Energy Efficiency and Renewable Energy, January 2004*.*

The approach for reducing the cost of these technologies as described in the *Solar Energy Technologies Multi-Year Program Plan*[42] is summarized below:

Table 2.3a: Photovoltaics R&D Focus Areas
• **Preliminary Investigation.** This area in the PV subprogram has historically been dominated by R&D in novel PV absorber materials and cell structures. Significant effort in this area has targeted building, maintaining, and expanding the science base and fundamental understanding of materials and device physics for optimum PV performance. • **Detailed Investigation.** Upon proof of concept in the preliminary investigation phase, the PV subprogram engages university and industry partners to expand the knowledge base of a new material/device/component/system to ensure that there is commercial interest and that the concept addresses a viable market need. • **Development.** Second-generation prototypes are developed and industry is supported in the development of pilot manufacturing processes. • **Testing and Validation**. This stage involves engaging industrial partners with full-scale manufacturing to field commercially viable products and to continue to implement R&D progress into manufacturing lines to reduce the timeline for program-supported R&D to reach products in the marketplace, as well as to implement the improvements necessary to reach the Solar Program's PV levelized cost of electricity targets.

Wind turbines can provide electricity for electrolysis using land based turbines in the near term and offshore turbines in the mid to long term. In most markets wind turbines depend on federal tax subsidies to be competitively priced with electricity produced from fossil fuels. The DOE Wind Program is performing technology research and development to reduce the cost of electricity on land and offshore to make wind power cost-competitive with fossil fuels without tax subsidies. The Wind Program is targeting commercially available turbine prototypes that produce electricity in moderate (class 4) winds for 3 ¢/kWh for onshore systems and 5 ¢/kWh for offshore systems by 2012 (in constant, levelized 2002 dollars).[43] The barriers to reducing the capital costs for these technologies as described in the *Wind Energy Program Multi-Year Plan* are summarized below.

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[42] *Solar Energy Technologies Program Multi-Year Technical Plan 2003-2007 and beyond,* DOE Office of Energy Efficiency and Renewable Energy, January 2004.

[43] *Wind Energy Program Multi-Year Program Plan 2005-2010*, DOE Office of Energy Efficiency and Renewable Energy, November 2004.

Table 2.3b: Wind Energy R&D Focus Areas

- **Land-Based Low Wind Speed Technology.** Lower the costs and improve the energy capture of wind turbine technologies for moderate wind regimes to make them competitive with other technologies through targeted research and private/public partnerships that address key issues such as increased turbine size, smart blade and rotor technologies, new drive train concepts, and manufacturing methods.
- **Offshore Turbine Technology.** Although the United States has little operational experience with offshore wind turbines, the large available offshore wind resource and its proximity to coastal load centers make it attractive for development. Offshore wind technology development will follow a path similar to land-based technology development, using private/public partnerships combined with targeted research focused on developing new design codes that can handle this unique operating environment; developing support structures and foundations; analyzing offshore wind resources; and assessing offshore environmental conditions and impacts. DOE is working on developing turbines and technologies for both shallow and transitional depth applications.
- **Distributed Wind Technologies.** Through private/public partnerships combined with targeted research for the development of small wind turbines that are 100 kW or less, DOE will work with industry to produce turbines that will achieve a cost of electricity that is competitive with retail rates. Distributed wind technologies could be colocated at hydrogen generation stations in either grid-connected or off-grid applications.
- **Wind Systems Integration.** Many utility decision makers, state regulators, and investment institutions are unfamiliar with wind technology and are cautious about implementing wind power as a utility generation asset. Principal among their concerns are potential system effects due to the current limitations in wind forecasting and the potential electrical system stability and dispatch implications. To ensure that wind’s needs are considered in regional transmission planning processes and to enhance wind’s compatibility with the nation’s energy needs over the long-term, DOE conducts research on grid integration and works to facilitate the adoption of equitable grid access and operational rules for wind in all major regional wind markets.
- **Technology Assistance and Coordination.** To reduce barriers to wind power acceptance and allow decision makers to make informed decisions, DOE provides both technical and general outreach information about wind energy technology and its potential benefits.
- **Emerging Markets.** There are several emerging markets for centralized and distributed wind technologies, including water desalination and hydrogen. Although wind turbines have not been optimized to produce hydrogen, wind turbines and electrolyzers could be colocated, sharing controllers and power conditioning systems. Additionally, the turbine could be designed to operate at power levels that match the load demands of the electrolyzer and its tower could be used for hydrogen storage.

DOE conducts ongoing research and development (R&D) on PEM, alkaline, and high-temperature solid-oxide electrolysis systems. Development includes advanced high-efficiency, low-cost alkaline and PEM electrolysis systems with an increased focus on the integration of electrolysis technologies and renewable electricity sources, and high-temperature electrolysis to reduce electrical requirement and improve overall system efficiency. Table 2.3c summarizes the electrolysis research focus areas and identifies current projects that are contributing to those objectives.

Table 2.3c: Electrolysis Research Focus Areas

Research Focus Areas	DOE Project Established[a]
Capital-cost-reduction objectives[b]: 1. Catalyst formulation and loading 2. Bipolar plate/flow field 3. Membrane expense and durability 4. Volume manufacturing of subsystems and modules 5. Overall design simplifications	Giner Electrochemical Systems Teledyne Energy Systems[d] Proton Energy Systems GE Global Research[e] Stirling Energy Systems[d]
System-efficiency-enhancing objectives[b]: 1. Reducing the ionic resistance of the membrane 2. Reducing other (parasitic) system energy losses 3. Reducing current density 4. Higher temperatures	Arizona State University Giner Electrochemical Systems Teledyne Energy Systems GE Global Research Ceramatec Materials and Systems Research
Grid electricity objectives: Integrated compression to reduce need for separate compressor.	Giner Electrochemical Systems Teledyne Energy Systems Proton Energy Systems
Renewable integration to optimize wind electrolysis[c]: 1. Integrated power control systems 2. Hydrogen storage	National Renewable Energy Laboratory Basin Electric Power Corporation

a These projects are established by DOE and include Congressionally directed projects that support research focus areas. All projects can be found in the Appendix.

b *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs*, Committee on Alternatives and Strategies for Future Hydrogen Production and Use, National Research Council and National Academy of Engineering, 2004, p. 221.

c Ibid, p. 227.

d This project performer was competitively selected but the project is currently not funded because of Congressionally directed projects that do not contribute to the program's goals.

e This project is a Congressionally directed project and was not competitively awarded.

2.4 Electrolysis Recommendations

Recent accomplishments in the electrolysis area include hydrogen production in a planar electrolysis stack at 2,000 psi (requires less compression energy), development of a new electrolysis system design with 50% part count reduction, and development of low-cost alkaline and PEM electrolysis systems for high pressure operation. A PEM electrolyzer stack has been installed and tested under variable operation to simulate renewable electricity source impacts.

DOE recommends (subject to appropriations):

1. Continuing research on electrolyzer materials to lower cost.
2. Continuing work on systems integration and optimization of wind turbine and electrolyzer systems.
3. Conducting limited demonstrations of renewable-energy electrolysis systems when research targets in technology roadmaps have been verified.

3.0 Thermochemical (Water Splitting) Hydrogen Production

Thermochemical water-splitting reaction cycles use compounds that can be reacted with water to produce hydrogen and then undergo one or more reactions to regenerate to the starting compound, completing the cycle before entering it again.

Solar concentrating systems currently provide the lowest-cost technology for solar electricity production, and they offer the potential to economically supply high-temperature heat for driving thermochemical processes for hydrogen generation.[44]

Figure 3.0: Solar Furnace with Tracking Heliostat

3.1 Thermochemistry Technology Status

High-temperature, solar-driven, thermochemical hydrogen production using water-splitting chemical cycles is in an early stage of research and, therefore, too immature to accurately assess current hydrogen cost. Solar concentrator technologies are available, but the capital costs are high, and they have not been linked to chemical reaction cycles. Of the over 150 potential chemical reaction cycles that have been identified in the literature, a small set has been selected for research with solar concentrators. The most promising are listed in Table 3.1a.

Table 3.1a: Promising Thermochemical Water Splitting Reaction Cycles[45]

	LHV* Efficiency (%)	Temperature (°C)	Device
Sulfuric acid cycles	35-43	900-1570	Dish/advanced tower
Metal sulfate cycles	35-46	1000-1100	Dish/advanced tower
Volatile and nonvolatile metal oxide cycles	42-49	1560-2000	Dish/advanced tower

* LHV is Lower Heating Value.

One example of a cycle is shown below.

Zinc Oxide Cycle: $ZnO \rightarrow Zn + \frac{1}{2} O_2$ $\approx 1800^{o}C$

$Zn + H_2O \rightarrow H_2 + ZnO$ $\approx 50^{o}C$

The Hydrogen Program goal is to verify, by 2015, the preliminary feasibility of solar-driven, high-temperature thermochemical hydrogen production to be competitive in the long term, by achieving the following technical targets for system energy efficiency and cost:

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[44] *Basic Research Needs for Solar Energy Utilization*, Office of Science, April 2005, p. 149.

[45] Solar Thermochemical Hydrogen (STCH) Generation Project, University of Colorado, see U.S. Department of Energy Hydrogen Program *2005 Annual Progress Report*, pp. 377-388.

Table 3.1b: Technical Targets for Solar-Driven, High-Temperature, Thermochemical Hydrogen Production[46]

Characteristics	Units	2010 Target	2015 Target[a]
Solar-driven high-temperature thermochemical cycle hydrogen cost	$/GGE H_2	6	3
Solar concentrator capital cost (installed cost)	$/m^2	150[b]	130
Process energy efficiency	%	40	45

a A follow-on technology validation phase will be required if these research targets are verified.

b *Assessment of Parabolic Trough and Power Tower Solar Technology Cost and Performance Forecasts* (SL-5641), Sargent & Lundy LLC Consulting Group for U.S. Department of Energy and National Renewable Energy Laboratory, May 2003. See www.solarpaces.org/csp_docs.htm. Also published as NREL/SR-550-34440.

These solar concentrator capital cost targets are consistent with the projections of an independent engineering assessment[47] for a growing market scenario. Included are the heliostat field and tower, but not the receiver, which may be substantially different for this thermochemical application. Activities within the Office of Energy Efficiency and Renewable Energy to study thermochemical cycles and high-temperature materials for hydrogen production are being closely coordinated with those of the Office of Nuclear Energy, Science, and Technology. The most research coordination is needed between solar- and nuclear-driven cycles at the lower temperatures, for example in the sulfuric acid cycle.

3.2 Thermochemistry Barriers

The most significant R&D needs are to (1) research and develop efficient and cost effective thermochemical cycles, (2) develop reactor designs and/or thermal systems that can be effectively linked to concentrating solar heliostats to provide the high-temperature heat source for the chemical reactions, and (3) develop materials that are cost-effective and compatible with the extreme chemical and thermal environments. A more detailed discussion can be found in *Basic Research Needs for the Hydrogen Economy*, Office of Science, May 2003, pp. 26-27; and *Basic Research Needs for Solar Energy Utilization*, Office of Science, April 2005, pp. 149-154.

If these efforts are successful, high-temperature thermochemical processes may provide a clean, efficient, and sustainable route for producing hydrogen from water.[48]

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[46] *Hydrogen, Fuel Cells & Infrastructure Technologies Program: Multi-Year Research, Development and Demonstration Plan - Planned program activities for 2003-2010*, DOE Office of Energy Efficiency and Renewable Energy, March 2005, p. 3-18.

[47] Ibid.

[48] Ibid, p. 3-9.

Table 3.2a: Barriers to High-temperature, Solar-driven, Thermochemical Production of Hydrogen[49]

- **High-Temperature Thermochemical Technology.** There are over 150 possible thermochemical cycles for solar-driven water splitting. These cycles need to be evaluated and ranked for their suitability. The most promising cycles need to be more fully explored and verified to down-select to a few cycles for research and development. Many of the cycles require developing technology to very rapidly quench high temperature reactions and/or separate hydrogen or other materials at high temperatures.
- **High-Temperature Robust Materials.** High temperatures are employed in these thermochemical systems. Cost-effective, durable materials are needed that can withstand these high temperatures and the thermal duty cycles present in solar concentrator systems.
- **Concentrated Solar Energy Capital Cost.** Concentrated solar energy collection is currently expensive and requires large areas of land. Improved, lower-cost solar concentrator/collection technology, including materials, is needed. The DOE Solar Program is addressing the following*:
    - **Performance Improvement.** This area of activity focuses R&D on improving the technical performance of systems by developing new system concepts, components, operational strategies, and materials. Activities include establishing a baseline and improving the reliability and performance of dish/engine systems.
    - **Cost Reduction.** Cost reduction, both for the systems and for individual system components, is not independent of performance, but may drive the selection of new components and/or systems and materials. Activities include field validation of next-generation trough receivers with improved thermal efficiencies that will reduce overall system costs.
    - **Deployment Support.** This focus area addresses the immediate needs of CSP industry partners who are in the process of fielding precommercial and commercial systems. These needs include issues associated with the manufacture, installation, design, and/or operation of systems and how they can best be addressed to make deployment successful. Activities include field validation of direct thermal storage technologies.
- **Coupling Concentrated Solar Energy and Thermochemical Cycles**. Coupling concentrated solar energy with thermochemical cycles presents many challenges. Receivers and reactors need to be developed and engineered. Cost effective approaches and systems to deal effectively with the diurnal nature of sunlight need to be researched and developed.

* *Solar Energy Technologies Program Multi-Year Technical Plan 2003-2007*, DOE Office of Energy Efficiency and Renewable Energy, January 2004.

Concentrating solar power (CSP) technologies can be used to generate the high temperatures needed for the thermochemical production of hydrogen. The DOE Solar Program has historically supported R&D on three CSP technologies: dish/Stirling systems, parabolic troughs, and power towers. The current cost of energy from CSP systems operating in the field (e.g., parabolic troughs) is in the 12 to 14 ¢/kWh range.[50] The long-term goal of the CSP subprogram is to develop solar plants that produce electricity that is competitive with electricity from conventional fossil power technologies in identified markets. The technology for parabolic trough and power tower systems is dispatchable due to the availability of thermal storage and the comparable value

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[49] *Hydrogen, Fuel Cells & Infrastructure Technologies Program: Multi-Year Research, Development and Demonstration Plan - Planned program activities for 2003-2010*, DOE Office of Energy Efficiency and Renewable Energy, March 2005, pp. 3-26 and 3-27.
[50] Ibid.

of electricity is in the range of 5 to 8 ¢/kWh (based on a natural gas price of $5/MMBtu).[51] The market for dish/Stirling systems during the next five years is central-station wholesale power generation, although longer-term markets will likely include niche opportunities such as utility grid support, remote power, and rural power.

3.3 Thermochemistry Research Focus Areas

Table 3.3: Thermochemistry Research Focus Areas

Research Focus Areas	DOE Project Established[a]
Research and develop efficient and cost-effective solar thermochemical cycles.	University of Colorado Science Applications International[b] University of Las Vegas Research Foundation[c]
Develop effective reactor designs and thermal heat transfer systems.	University of Colorado Science Applications International[b] University of Las Vegas Research Foundation[c]
Develop lower cost heliostat technology.	Sandia National Laboratories
Identify or develop new materials or processes that are compatible with very high temperature reaction chemistry.	University of Colorado

a These projects are established by DOE and include Congressionally directed projects that support research focus areas. All projects can be found in the Appendix.

b This project performer was competitively selected but the project is currently not funded because of Congressionally directed projects that do not contribute to the program's goals.

c This project is a Congressionally directed project and was not competitively awarded.

3.4 Thermochemistry Recommendations

Recent accomplishments in the thermochemical cycle area include screening over 150 cycles identified in the literature and down-selecting to the most promising 9 cycles for research efforts. The selected cycles fall into five families; sulfur-based, volatile metals, metal oxides, ferrites, and sulfates. Also, the high temperature phase (approximately 1800°C) of two of these promising cycles, the zinc oxide volatile metal cycle and the manganese oxide cycle were successfully demonstrated in the laboratory for the first time.

DOE recommends, subject to appropriations, continuing to evaluate the use of thermochemical cycles for hydrogen production driven by solar concentrating devices.

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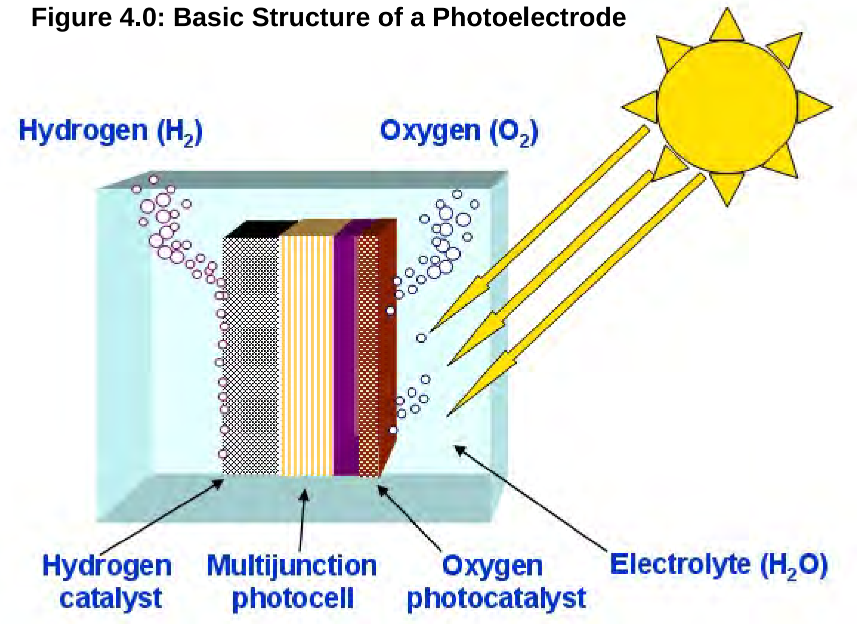
[51] *Solar Energy Technologies Program Multi-Year Technical Plan 2003-2007*, DOE Office of Energy Efficiency and Renewable Energy, January 2004.

4.0 Photoelectrochemical Hydrogen Production

The direct photoelectrochemical (PEC) splitting of water is a one-step process for producing hydrogen using solar irradiation; water is split directly upon illumination. The basic photoelectrochemical device consists of a semiconductor material immersed in an aqueous solution configured such that it can be illuminated by direct sunlight. Photoelectrochemical devices combine solar PV and electrolysis into a single monolithic device. This provides the possibility of higher conversion efficiency and lower cost for solar-driven hydrogen generation from water as compared to standard PV/electrolysis.

Figure 4.0: Basic Structure of a Photoelectrode



4.1 Photoelectrochemistry Technology Status

Photoelectrochemical hydrogen production is in an early stage of development; therefore, the current hydrogen cost cannot be accurately assessed. Its future depends on a breakthrough in developing photoelectrochemical materials that are durable and efficient in producing hydrogen. Known light-absorbing semiconductor materials have either low efficiency (1%-2%) or low durability in a liquid electrolytic environment.[52]

Research is progressing to:

- Study high-efficiency materials and low-cost, durable materials to attain the basic scientific understanding that will be needed to integrate the necessary functionality into a single material.
- Develop multijunction devices that incorporate multiple material layers to achieve efficient water splitting.

Methods of manufacturing these systems also need to be developed in conjunction with the materials and device research.

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[52] *Basic Research Needs for Solar Energy Utilization*, Office of Science, April 2005, p. 117.

The Hydrogen Program goal is to verify, by 2015, the preliminary feasibility of photoelectrochemistry to be competitive in the long term, by achieving the following technical targets for system energy efficiency and durability:

Table 4.1: Technical Targets for Photoelectrochemical Hydrogen Production[53]

Characteristics	Units	2003 Status	2010 Target	2015 Target (Go/No-Go Decision)
Usable semiconductor bandgap	eV	2.8	2.3	2.0
Chemical conversion process efficiency	%	4	10	12
Plant solar-to-hydrogen efficiency	%	not available	8	10
Plant durability	hr	not available	1000	5000

Hydrogen cost will be evaluated as part of a research and development go/no-go decision in 2015, to determine whether future funding is warranted. The targets in this table are for research tracking. The final target for this technology is to achieve costs that are competitive with future vehicle and fuel technologies. Commercialization targets beyond 2015 are estimated to be 16% plant solar-to-hydrogen (STH) efficiency and 15,000 hours plant durability.[54]

The primary research challenge is that, while a range of materials and material systems have met individual 2010 targets for chemical efficiency or durability, no single material or system has simultaneously met efficiency and durability targets.

4.2 Photoelectrochemistry Barriers

High-efficiency, durable photoelectrochemical materials need to be developed, fabricated into devices, and engineered into complete photoelectrochemical reactor systems. Coupling computational science with experimental search techniques represents a promising pathway for discovering new photoelectrodes with specific and unique properties. A more detailed discussion can be found in *Basic Research Needs for the Hydrogen Economy*, Office of Science, May 2003, pp. 22-23; and *Basic Research Needs for Solar Energy Utilization*, Office of Science, April 2005, p. 117.

Nanoscale synthesis techniques hold extraordinary promise for the development of new materials for PV/electrolysis processes. Fundamental research in which modeling and synthesis are closely coupled have the potential of producing nanostructures with tailored bandgaps optimized for hydrogen production. These tailored nanoscale synthesis techniques can also provide more highly integrated PEC devices that combine multiple functions in an efficient, robust, cost-effective system that utilizes the full solar spectrum.

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[53] *Hydrogen, Fuel Cells & Infrastructure Technologies Program: Multi-Year Research, Development and Demonstration Plan - Planned program activities for 2003-2010*, DOE Office of Energy Efficiency and Renewable Energy, March 2005, p. 3-18.

[54] Ibid.

Technology barriers are as follows:

Table 4.2: Photoelectrochemical Hydrogen Production[55] Barriers

- **Materials Efficiency.** Materials with smaller bandgaps more efficiently utilize the solar spectrum, but are often less energetically favorable for hydrogen production because of the band edge mismatch with respect to either hydrogen or oxygen redox potentials. Materials with appropriate bandedge and bandgap for hydrogen production must be developed.
- **Materials Durability.** Durable materials with the appropriate characteristics for photoelectrochemical hydrogen production that meet the Hydrogen Program goals have not been identified. The high-efficiency materials currently available corrode quickly during operation, and the most durable materials are very inefficient for hydrogen production.
- **Bulk Materials Synthesis.** Fabrication techniques for materials identified to have potential for high efficiency, durability, and low cost need to be developed on scales consistent with implementation in commercial reactors.
- **Device Configuration Designs.** Hybrid and other device designs that combine multiple layers of materials could address issues of durability and efficiency. Techniques are needed for manufacturing appropriate photoelectrochemical materials in these device configurations at commercial scales.
- **Systems Design and Evaluation.** System designs incorporating the most promising device configurations, and using cost-effective, hydrogen-impermeable, transparent materials are also needed to implement photolytic production routes. The complete systems evaluation will need to consider a range of important operational constraints and parameters, including the diurnal operation limitations and the effects of water purity on performance and lifetime. Engineering options need to be carefully analyzed to minimize capital requirements.

4.3 Photoelectrochemistry Research Focus Areas

Research on new materials and material systems for photoelectrochemistry is being conducted at universities, national laboratories, and industrial companies. A variety of materials comprising the spectrum of efficiency and durability is being investigated concurrently. A materials database is being established to enable researchers to build upon nationwide findings in the search for suitable photoelectrochemical materials. Table 4.3 identifies research focus areas, and projects that are contributing to DOE’s objectives.

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[55] *Hydrogen, Fuel Cells & Infrastructure Technologies Program: Multi-Year Research, Development and Demonstration Plan - Planned program activities for 2003-2010*, DOE Office of Energy Efficiency and Renewable Energy, March 2005, pp. 3-25 and 3-26.

Table 4.3: Photoelectrochemistry Research Focus Areas

Research Focus Areas	DOE Project Established[a]
Materials efficiency	GE Global Research University of California, Santa Barbara University of Nevada, Las Vegas[b] SRI Midwest Optoelectronics National Renewable Energy Laboratory MV Systems Inc.[c]
Materials durability	GE Global Research University of California, Santa Barbara University of Nevada, Las Vegas[b] SRI Midwest Optoelectronics MV Systems Inc.[c] National Renewable Energy Laboratory
Bulk materials synthesis	University of Nevada, Las Vegas[b] GE Global Research MV Systems Inc.[c]
Device configuration designs	University of Nevada, Las Vegas[b] GE Global Research National Renewable Energy Laboratory University of Toledo MV Systems Inc.[c]
Basic research for solar production	Colorado State University California Institute of Technology University of Arizona University of California, Santa Cruz Pennsylvania State University Purdue University University of Washington Nanoptek Corporation Virginia Polytechnic Institute Brookhaven National Laboratory Pacific Northwest National Laboratory National Renewable Energy Laboratory

[a] These projects are established by DOE and include Congressionally directed projects that support research focus areas. All projects can be found in the Appendix.

[b] This project is a Congressionally directed project and was not competitively awarded.

[c] This project performer was competitively selected but the project is currently not funded because of Congressionally directed projects that do not contribute to the program's goals.

4.4 Photoelectrochemistry Recommendations

Recent accomplishments in the photoelectrochemical area include demonstrating that tungsten trioxide can be deposited at low temperatures (<300°C) on low cost hybrid devices while maintaining high (2.5 mA/cm^2) photocurrent performance and achieving a projected 1,000 hours durability with new gallium phosphide nitride material based on accelerated testing. Photoelectrochemistry has been reviewed by the National Research Council, which identified the direct splitting of water as an important pathway for research.[56]

DOE recommends (subject to appropriations):

1. Continuing basic research into photoprocesses and catalytic reactions.
2. Continuing applied research and development on photoelectrochemical materials and devices.
3. Designing and evaluating systems (upon attainment of the 2015 interim goals).

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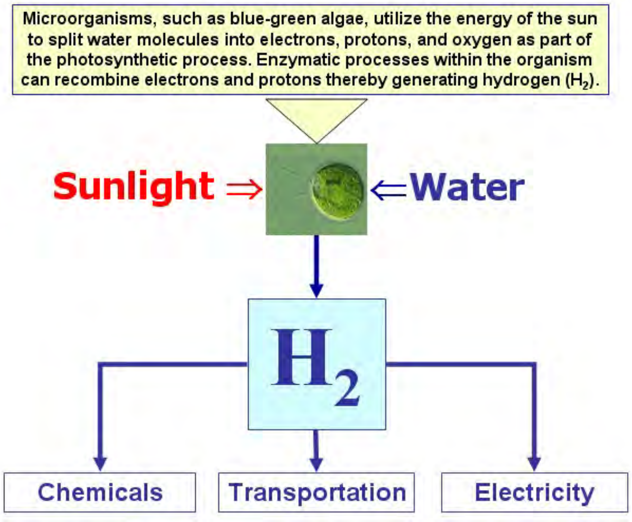
[56] *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs*, Committee on Alternatives and Strategies for Future Hydrogen Production and Use, National Research Council and National Academy of Engineering, 2004, p. 238.

5.0 Photobiological Hydrogen Production

Organisms can use photosynthetic pathways to produce hydrogen from organic compounds or water. These pathways require rational design, strain development, and strain optimization in unicellular green algae and cyanobacteria to facilitate efficient production of hydrogen from solar resources. Photosynthetic bacteria provide another pathway of interest, but this technology is in a very early research stage and is not addressed in detail in this report.

Figure 5.0: Photobiological Pathway to Hydrogen Production



Microorganisms, such as blue-green algae, utilize the energy of the sun to split water molecules into electrons, protons, and oxygen as part of the photosynthetic process. Enzymatic processes within the organism can recombine electrons and protons thereby generating hydrogen (H_2).

5.1 Photobiology Technology Status

Photobiological hydrogen production is in an early stage of research; therefore, the current hydrogen cost cannot be accurately assessed. This pathway presents several technical challenges, beginning with identifying or engineering microorganisms that can produce hydrogen at high rates and high conversion efficiencies. Photobiological hydrogen production does not require high-purity water and toxic or polluting byproducts are not generated.[57]

Photobiological hydrogen production is theoretically more efficient than using solar energy to grow biomass and then producing hydrogen from the biomass because it avoids inefficiencies in the biochemical steps involved in biomass production. However, such efficient biological capability does not occur in any known naturally occurring organism. Fundamental molecular research is needed to identify and improve the limiting factors in order to fully evaluate this approach for continuous hydrogen production under sunlight.[58]

Although photobiological hydrogen production has the potential to contribute significantly to a future hydrogen economy, there are major challenges to be overcome before a pilot-scale photobiological system can be evaluated. Substantial bioengineering efforts are being undertaken to identify or develop microorganisms with a robust metabolic pathway including improved kinetics for hydrogen production and efficiencies in the conversion of light energy to hydrogen.[59]

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[57] *Hydrogen, Fuel Cells & Infrastructure Technologies Program: Multi-Year Research, Development and Demonstration Plan - Planned program activities for 2003-2010*, DOE Office of Energy Efficiency and Renewable Energy, March 2005, p. 3-9.

[58] *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs*, Committee on Alternatives and Strategies for Future Hydrogen Production and Use, National Research Council and National Academy of Engineering, 2004, p. 233.

[59] Ibid.

The Hydrogen Program goal is to verify, by 2015, the preliminary feasibility of biological production of hydrogen to be competitive in the long term with other technologies, by achieving the following technical targets for system sustainability:

Table 5.1: Technical Targets for Photolytic Biological Hydrogen Production from Water[60]

Characteristics	Units	2003 Status	2010 Target	2015 Target (Go/No-Go Decision)
Utilization efficiency of incident solar light energy (E0*E1)	%	10	15	20
Efficiency of incident light energy to hydrogen from water (E0*E1*E2)	%	0.1	1	5
Duration of continuous photoproduction	time units	not available	30 min	4 h
Oxygen tolerance (half life in air)	time units	1 s	10 min	2 h

Note: Efficiencies relate to the following conversion steps: $\text{Solar light} \xrightarrow{E0} \text{Absorbed light} \xrightarrow{E1} \text{Electrons} \xrightarrow{E2} H_2$

In the table, E0 reflects the light collection efficiency of the photoreactor and the fact that only a fraction of solar incident light is photosynthetically active (theoretical maximum is 45%). E1 is the efficiency with which algae convert the energy of absorbed photons to chemical energy (i.e., chemical potential; theoretical maximum is 71%). E0*E1 represents the efficiency of conversion of incident solar light to chemical potential (theoretical maximum is 32%).

E2 reflects the efficiency with which the chemical potential generated by the absorbed photons is converted to hydrogen (theoretical maximum is 41%). E0*E1*E2 represents the efficiency of conversion of incident solar light to hydrogen (theoretical maximum is 13% when water is the substrate); all figures are peak efficiencies.

Hydrogen cost will be evaluated as part of a research and development go/no-go decision in 2015, to determine whether future funding is warranted. The targets in this table are for research tracking. The final targets for this technology are to reach costs that are competitive with future vehicle and fuel technologies.

A primary research challenge to achieve continuity in hydrogen production, in the case of photobiological hydrogen production, is to develop a biological system that operates under aerobic conditions, either through an oxygen-tolerant hydrogenase, or through manipulation of the concomitant oxygen-evolving activity of the cultures. In the case of photosynthetic bacteria, a major research challenge is to reduce biological mechanisms that are competitive with the hydrogenase to produce more hydrogen and fewer coproducts.

Four barriers specific to the biological enzyme that catalyzes the formation of hydrogen (hydrogenase) currently challenge biology-based photosynthetic hydrogen production: (1) restriction of photosynthetic hydrogen production due to accumulation of a proton gradient, (2) competitive inhibition of photosynthetic hydrogen production by carbon dioxide, (3) requirement for bicarbonate binding for efficient photosynthetic activity, and (4) competitive drainage of

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[60] *Hydrogen, Fuel Cells & Infrastructure Technologies Program: Multi-Year Research, Development and Demonstration Plan - Planned program activities for 2003-2010*, DOE Office of Energy Efficiency and Renewable Energy, March 2005, p. 3-16.

electrons by oxygen in algal hydrogen production. While engineering these changes in biological systems to address these challenges may be possible, understanding the molecular level processes that are employed by biological systems would open the door to designing nonbiology-based photosynthetic processes so these barriers could be circumvented. Harnessing nature's processes in biomimetic materials and systems would provide the needed improvements in efficiency and robustness that would make these processes more broadly applicable in an alternative energy strategy.

5.2 Photobiology Barriers

A number of technologies for biological hydrogen production are available, but they are currently in the very early stages of development. Technical barriers related to each individual technology must be overcome, integrated models must be developed, and barriers related to an integrated system must be identified before a system can be engineered. A more detailed discussion can be found in *Basic Research Needs for the Hydrogen Economy*, Office of Science, May 2003, pp. 89-94; and *Basic Research Needs for Solar Energy Utilization*, Office of Science, April 2005, pp. 121-133.

Table 5.2: Barriers to Biological Production of Hydrogen[61]

- **Light Utilization Efficiency.** The microorganisms used for photobiological hydrogen production possess large arrays of light-capturing antenna pigment molecules. Under bright sunlight, pigment antennae absorb much more light than can be utilized by the photosynthetic electron apparatus, resulting in heat dissipation and loss of up to 80% of the absorbed sunlight. Research is needed to identify ways to increase the light conversion efficiency, including the identification of better and/or modified photosynthetic organisms for hydrogen production.
- **Rate of Hydrogen Production.** The current hydrogen production rate from photosynthetic microorganisms is too low for commercial viability. The low rates have been attributed to (a) the nondissipation of a proton gradient across the photosynthetic membrane, which is established during the electron transport from water to the hydrogenase (the hydrogen-producing enzyme) under anaerobic conditions, and (b) the existence of competing metabolic flux pathways for reductant. Genetic means to overcome the restricting metabolic pathways, such as the insertion of a proton channel across the thylakoid membrane, must be used to significantly increase the rate of hydrogen production. Under aerobic conditions with an oxygen-tolerant hydrogenase catalyzing hydrogen production, the competition between carbon-dioxide fixation and hydrogenase will have to be addressed.
- **Continuity of Photoproduction.** Hydrogen-producing algae coproduce oxygen, which inhibits the hydrogenase enzyme activity. This inhibition needs to be alleviated, possibly by (a) identifying or engineering a less oxygen-sensitive enzyme; (b) separating the oxygen and hydrogen production cycles; or (c) affecting the ratio of photosynthesis to respiration (P/R) by a variety of means, such that oxygen does not accumulate in the medium, the quantum yield of photosynthesis is maintained, and full hydrogenase activity is achieved.
- **Systems Engineering.** System requirements for cost-effective implementation of photolytic hydrogen production technologies have not been adequately evaluated. Analysis and research are needed on inexpensive/transparent materials for hydrogen containment, hydrogen collection systems, prevention of the buildup of hydrogen/oxygen gas mixtures, separation of coproduced hydrogen and oxygen gases, continuous bioreactor operation, monoculture maintenance, land area requirements, and capital costs.
- **Diurnal Operation Limitations.** Photolytic processes are discontinuous because they depend on sunlight, which is unavailable at night and available only at low intensities on cloudy days. This results in increased capital costs for larger facilities to accommodate higher short-term production rates and larger hydrogen storage needs. Engineering options need to be carefully analyzed to minimize capital requirements.

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[61] *Hydrogen, Fuel Cells & Infrastructure Technologies Program: Multi-Year Research, Development and Demonstration Plan - Planned program activities for 2003-2010*, DOE Office of Energy Efficiency and Renewable Energy, March 2005, pp. 3-22 and 3-23.

5.3 Photobiology Research Focus Areas

DOE is funding research on photobiological pathways to hydrogen at a number of institutions. Research is being directed at the most critical issues involving process efficiency and duration of continuous production.

Table 5.3: Photobiology Research Focus Areas

Research Focus Areas	DOE Project Established[a]
Light utilization efficiency	University of California, Berkeley
Rate of hydrogen production	Oak Ridge National Laboratory Montana State University[b]
Continuity of photoproduction	National Renewable Energy Laboratory J. Craig Venter Institute
Systems engineering	Advanced Bionutrition Corporation[b] National Renewable Energy Laboratory
Basic research for bio-inspired production	University of Washington University of Georgia Pennsylvania State University University of Pennsylvania University of Oklahoma National Renewable Energy Laboratory
Diurnal operation limitations	None

a These projects are established by DOE and include Congressionally directed projects that support research focus areas. All projects can be found in the Appendix.

b This project performer was competitively selected but the project is currently not funded because of Congressionally directed projects that do not contribute to the program's goals.

5.4 Photobiology Recommendations

Recent accomplishments in the photobiological area include increased photobiological efficiency of absorbed sunlight energy to approximately 15% (compared to 5% in 2003) and 40%-50% increase in oxygen tolerance achieved.

DOE recommends (subject to appropriations):

1. Continuing a combination of basic and applied research and development to improve the scientific basis and overcome the technical challenges facing biological pathways. These pathways offer the promise of sustainable hydrogen production routes for the future.
2. Upon reaching interim (2010) technical targets, investigating the feasibility of integrating different biological hydrogen production processes in order to maximize solar spectral utilization, efficiently recycle biomass and fermentation products, and improve the economics of the process including overcoming diurnal operation limitations.

6.0 Demonstrating Hydrogen Production from Solar and Wind Energy

The Program includes learning demonstration projects that are important to technology development because they help determine economic competitiveness under real operating conditions. There are two purposes for these demonstrations: (1) to provide feedback to the research program, and (2) to validate whether the technical targets (cost effectiveness, etc.) are achieved. Once these targets are achieved, the technologies will be evaluated by industry for further development and commercialization.

Specific demonstration projects include the following.

6.1 Integration Test Sites

1. *National Renewable Energy Laboratory (NREL) (Golden, Colorado)*

   The Program recently established a hydrogen electrolysis test facility located at NREL's National Wind Technology Center, to serve as the key research and development facility for optimizing the integration of renewable/electrolysis systems. The facility is serving as an independent test site for industry and enabling collaborative research among national laboratories, academia, and industry. NREL is negotiating a cooperative research and development agreement with Xcel Energy, one of the nation's largest utilities, to develop and optimize a hydrogen/electricity cogeneration system powered by wind, with the goal to demonstrate such systems in Colorado and Minnesota. Other participants in the overall effort to develop direct-coupled renewable/electrolysis cogeneration systems currently include the Universities of Minnesota, North Dakota, and Hawaii; Northern Power Systems; Basin Electric; and Proton Energy Systems.

2. *Wind to Hydrogen Energy Pilot Project (Minot, North Dakota)*

   Basin Electric Power Corporation is developing and installing a wind-electrolysis-based hydrogen fueling station at the North Dakota State University (NDSU) North Central Research Extension Center located near Minot, ND. The specific goal for the project is to better understand the advantages, challenges, and technical hurdles related to dynamically scheduling wind power from geographically disparate locations to power a hydrogen production facility. Operational considerations of hydrogen production and delivery systems, especially under nonsteady-state operating conditions induced from dynamic scheduling, will be assessed.

3. *SunLab (Albuquerque, New Mexico and Golden, Colorado)*

   The National Solar Thermal Test Facility (NSTTF) at Sandia National Laboratories (SNL) and the High Flux Solar Furnace (HFSF) at NREL provide valuable resources for the advancement of concentrating solar technologies. NSTTF is equipped with a central tower and 222 heliostats, a 16-kilowatt solar furnace, a trough rotating platform facility, engine test facility, and distributed receiver test facility with two 75-kilowatt parabolic dishes. The 10-kilowatt HFSF uses a tracking heliostat and 25 hexagonal mirrors to concentrate solar radiation and can provide flux at 2,000 to 20,000 suns. These facilities can be used to test thermochemical hydrogen production.

6.2 Power Parks

1. *Arizona Public Service: Hydrogen Power Park Business Opportunities Concept Project (Phoenix, Arizona)*

   Arizona Public Service (APS) operates an existing hydrogen fueling station in Phoenix, AZ. This facility is incorporated into the power park project to create a real-world basis for evaluating hydrogen production and vehicle refueling, and gaining experience with siting and permitting such facilities. APS has developed four business case options to be evaluated. Testing model components will create data that researchers can use to evaluate the economic case for these four power park options. APS will evaluate wind and solar electrolysis systems that will create a database for renewable energy integration.

2. *Hawaii Natural Energy Institute: Hawaii Hydrogen Power Park (Oahu, Hawaii)*

   The University of Hawaii's Hawaii Natural Energy Institute (HNEI) in Oahu, HI, will develop and operate a test bed for validation and characterization of hydrogen technologies in an operations mode that will:

   - Integrate a renewable energy source (such as wind, solar, and geothermal) on the Big Island of Hawaii with an advanced low-cost electrolyzer, fuel cell, and hydrogen-fueled internal combustion engine to power a building.
   - Collect actual cost and engineering data.
   - Conduct outreach to local authorities and the general public.

   HNEI will select a showcase site which contributes to outreach objectives.

3. *DTE Energy: DTE Energy Hydrogen Technology Park (Southfield, Michigan)*

   DTE has developed, installed, and is operating a hydrogen coproduction facility capable of delivering 500 kWh/day of on-site electricity and 15 kg/day of compressed hydrogen for vehicle refueling. By incorporating the most commercially representative units into a complete system operating under various conditions, this approach is designed to validate system and component technical targets and provide feedback to DOE on the commercial viability of these hydrogen energy systems. Renewable electricity systems using solar, wind, and biomass resources will be evaluated.

6.3 Hydrogen Fueling Stations

1. *Hydrogen Commercialization for the 21st Century (Thousand Palms, California)*

   Sunline Transit Agency, located in Palm Desert, CA, served as the world’s first hydrogen generation/storage/fueling facility built by a public utility. The project integrated renewable hydrogen generation via PV-electrolysis into a public-access fueling station. Key lessons learned from this demonstration included system design and optimization, site permitting, staff training and public education. The performance data and operational experience gained from the 37-kilowatt PV array and two on-site electrolyzers serves as a valuable input into ongoing and planned demonstrations.

2. *Ford/BP: Hydrogen Fuel Cell Vehicle and Infrastructure Demonstration (Orlando, Florida)*

   Under Ford's vehicle and infrastructure learning demonstration project, BP will integrate renewable power generation into their hydrogen vehicle fueling station in Orlando, Florida. Electricity generated from photovoltaics and wind power will be used to produce hydrogen via electrolysis for vehicle fueling.

   This approach includes the following benefits:

   - Allows assessment of the economic benefits of integrating hydrogen production and power generation.
   - During peak periods hydrogen will be used to provide electricity to the grid.
   - Integrating power and fuel generation will allow researchers to assess the potential of renewable-based hydrogen to achieve DOE cost targets.

The Program's plans call for a commercial readiness demonstration program to begin in 2009. This project will serve as Phase 3 of the vehicle and infrastructure learning demonstration program. Increased emphasis will be placed on renewable generation technologies and will include a key milestone to validate an integrated renewable electrolysis system to produce hydrogen at a cost less than $3 per gge. Assuming a successful go/no-go decision on high-temperature electrolysis in 2007, the Program will evaluate opportunities for including a solar concentrator/high-temperature electrolysis system.[62]

7.0 Funding

As shown in Table 7.0a, DOE is managing approximately $130 million annually in wind and solar technologies, with the goal of making the electricity more affordable. High electricity cost is a major commercialization barrier to electrolytic hydrogen production.

Table 7.0a: EERE Solar and Wind Technology Funding

	FY05 ($M)	FY06 Request Funding ($M)[a]
Solar	84.2[b]	84.0[c]
Wind	40.6[d]	44.2
Total	124.8	128.2

a Estimated FY06 funding decision will be based on merit review of each project in the portfolio and appropriated funding level. This report pre-dates decisions made on how FY2006 appropriations will be distributed to key activities within each program.
b FY05 $6.0 M is for concentrating solar power.
c FY06 $6.0 M is for concentrating solar power.
d $0.5 M of this funding is for the Basin Electric Congressionally directed project.

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[62] *Hydrogen, Fuel Cells & Infrastructure Technologies Program: Multi-Year Research, Development and Demonstration Plan - Planned program activities for 2003-2010*, DOE Office of Energy Efficiency and Renewable Energy, March 2005, p. 3-103.

Under the DOE Hydrogen Program and in support of the President's Hydrogen Fuel Initiative, the Offices of Science and Energy Efficiency and Renewable Energy are collaborating on the basic and applied research to make renewable-based hydrogen market-competitive. Table 7.0b shows annual funding of approximately $22 million.

Table 7.0b: Renewable Hydrogen Production R&D Funding[63]

	FY05 ($M)	FY06 Request Funding ($M)[a]
Office of Science	6.27	2.9[b]
EERE:		
Electrolysis	4.5[c]	4.1
Thermochemistry	3.3[d]	0.58
Photoelectrochemistry	5.7[e]	2.4
Photobiology	2.1	2.1
Total	21.87	12.08

a Estimated FY06 funding decision will be based on merit review of each project in the portfolio and appropriated funding level. This report pre-dates decisions made on how FY2006 appropriations will be distributed to key activities within each program.
b Does not Include funds for projects awarded through an FY2005 solicitation (awards were announced after release of FY2006 budget request).
c Includes SBIR and $1.1 M in Congressionally directed projects.
d Includes $3.2 M in Congressionally directed projects.
e Includes $3.9 M in Congressionally directed projects.

Total DOE funding for these projects is approximately $99 million and is subject to appropriations. Projects are shown in the Appendix.

In addition, there are several projects within the Office of Nuclear Energy, Science, and Technology that are developing high-temperature thermochemical hydrogen production technologies that could be used for solar applications.

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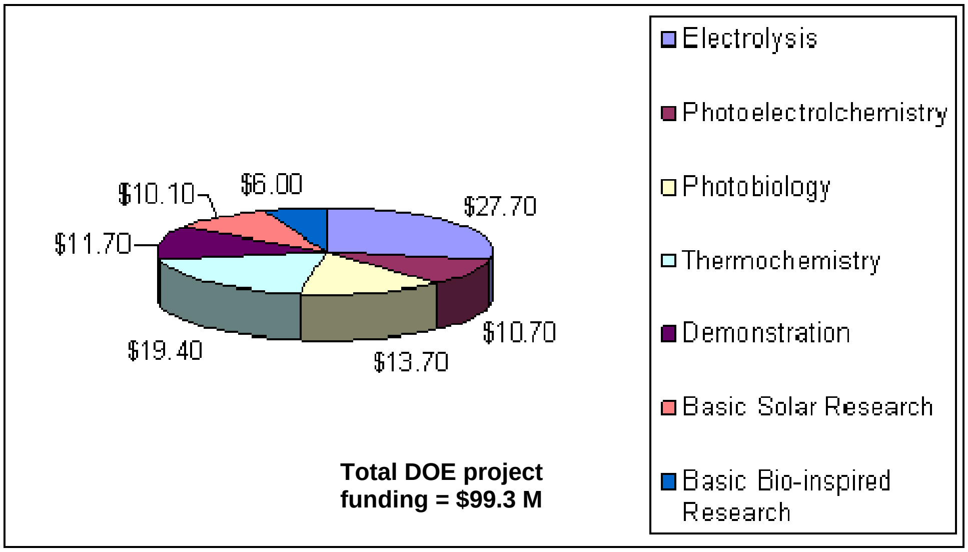
[63] Excludes biomass-derived hydrogen work and demonstrations. FY06 funding subject to appropriations.

Figure 7.0: DOE Renewable Hydrogen Production Portfolio (Multiyear, $ millions)



Total DOE project funding = $99.3 M

8.0 University Program Support

DOE actively engages the university community in developing both solar and wind technologies for producing hydrogen. This is done through competitive solicitations directly to the university community as well as through competitive solicitations to industry and national laboratories with the opportunity for universities to partner on teams. In addition, the national laboratories solicit participation by the university community in their research projects. Postdoctoral positions and positions for both graduate and undergraduate students are available at national laboratories to study solar and wind technologies to produce hydrogen. Approximately 15% of the EERE Hydrogen Program funding in FY05 went to universities.[64] Examples of university participation are shown in the Appendix.

9.0 Progress in Establishing Projects Required Under Section 812

Table 9.0 provides the status of DOE's progress in addressing the requirements in section 812 of the Energy Policy Act of 2005.

Table 9.0: DOE's Progress in Establishing Projects and Programs Required Under Section 812 (Solar and Wind Technologies)

Energy Bill Requirement	Status
(a)(2) Provide for the establishment of five projects in geographic areas that are regionally and climatically diverse to demonstrate the production of hydrogen at solar energy facilities, including one demonstration project at a national laboratory or institution of higher education.	The following projects have been established: • National Renewable Energy Laboratory (Colorado) • Arizona Public Service (Arizona) • University of Hawaii (Hawaii) • DTE Energy (Michigan) • Ford/BP (Florida) • Sandia National Laboratories (New Mexico) • Sunline Transit Agency (California)

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[64] U.S. Department of Energy Hydrogen Program, # 5015.

Table 9.0 (continued)	
Energy Bill Requirement	**Status**
(a)(3) Establish a program: (a)(3)(A) to develop optimized concentrating solar power devices that may be used for the production of both electricity and hydrogen. (a)(3)(B) to evaluate the use of thermochemical cycles for hydrogen production at the temperatures attainable with concentrating solar power devices.	DOE's Solar Technologies and Hydrogen, Fuel Cells, and Infrastructure Technologies Programs are developing concentrating solar power devices and evaluating their use for thermochemical cycles for producing hydrogen. Projects include work at: • Sandia National Laboratories and the National Renewable Energy Laboratory • University of Colorado • Stirling Energy Systems, Inc. • Science Applications International Corporation • University of Nevada, Las Vegas
(a)(4) Coordinate with activities sponsored by the Department's Office of Nuclear Energy, Science, and Technology on high-temperature materials, thermochemical cycles, and economic issues related to solar energy.	DOE is coordinating these activities under its *Hydrogen Posture Plan*.
(a)(5) Provide for the construction and operation of new solar power devices or solar power generation facilities that produce hydrogen either concurrently with, or independently of, the production of electricity.	Further technology advancements need to be validated prior to decision to construct new facilities. • Arizona Public Service • DTE Energy
(a)(6) Support existing facilities and programs of study related to concentrating solar power devices.	DOE's Solar Technologies Program is supporting projects at Sandia National Laboratories and the National Renewable Energy Laboratory.
(a)(7) Establish a program: (a)(7)(A) to develop methods that use electricity from photovoltaic devices for the onsite production of hydrogen, such that no intermediate transmission or distribution infrastructure is required or used and future demand growth may be accommodated. (a)(7)(B) to evaluate the economies of small-scale electrolysis for hydrogen production. (a)(7)(C) to study the potential of modular photovoltaic devices for the development of a hydrogen infrastructure, the security implications of a hydrogen infrastructure, and the benefits potentially derived from a hydrogen infrastructure.	DOE's Hydrogen, Fuel Cells, and Infrastructure Technologies and Solar Technologies Programs have established projects on distributed generation of hydrogen from photovoltaic devices: • National Renewable Energy Laboratory • Giner Electrochemical Systems • Avalence LLC
(b)(2) Provide for the establishment of five projects in geographic areas that are regionally and climatically diverse to demonstrate the production of hydrogen at existing wind energy facilities, including one demonstration project at a national laboratory or institution of higher education.	The following projects have been established: • National Renewable Energy Laboratory (Colorado) • Basin Electric (North Dakota) • Arizona Public Service (Arizona) • University of Hawaii (Hawaii) • DTE Energy (Michigan)

10.0 Conclusions

1. The United States has an abundance of renewable solar and wind resources that are sufficient to produce enough hydrogen for its entire fleet of vehicles.
2. Development of domestic solar- and wind-based hydrogen production technologies creates opportunities to increase energy security by providing an alternative to imported oil and to improve the environment by reducing criteria and carbon dioxide emissions.
3. Multiple pathways are being pursued. Hydrogen can be produced from solar and wind energy by using electrolysis and by directly splitting water using photoelectrochemistry, photobiological organisms (and other pathways), and heat-driven chemical reaction cycles.
4. Electrolyzer technology needs further development to overcome commercialization barriers. Wind energy is the most attractive source of electricity for distributed hydrogen production because the cost of wind-generated electricity can be less than 4 ¢/kWh. With successful electrolyzer development and a positive 2015 industry commercialization decision,[65] hydrogen produced on-site (distributed) at fueling stations or at production facilities in or near major cities from wind-based electrolysis could be competitive in the transition to a hydrogen economy. This distributed approach eliminates the need for investment in a national hydrogen delivery infrastructure prior to vehicle mass market penetration and offers important flexibilities via the electric power system for how renewable electric sources could be best harnessed to produce hydrogen.
5. Distributed hydrogen production from solar photovoltaic energy will not be competitive (based on Energy Information Agency gasoline forecasts) for the "transition" period because electricity costs will be too high (i.e., 2020 goal of 6 to 8 ¢/kWh for commercial systems). Electricity cost needs to be less than 5 ¢/kWh based on the 2015 forecast for untaxed gasoline price.
6. By 2030, centralized wind- and solar-based hydrogen systems (electrolysis and other pathways) can produce enough hydrogen to virtually eliminate petroleum energy use and greenhouse gas emissions from the light-duty transportation sector assuming fuel cell vehicles displace all internal combustion engine and diesel vehicles. Centralized systems also assume that pipeline delivery systems are available in the 2030 timeframe.
7. Photoelectrochemical and photobiological hydrogen production pathways are at a very immature state of development and require much more basic and applied research before feasibility can be determined. The program has scheduled go/no-go decisions for 2015 for each of these pathways.
8. Significantly more development is necessary for solar-driven thermochemical hydrogen production technology to reach its 2015 research targets.
9. Detailed technology roadmaps have been established for all solar- and wind-based hydrogen production pathways and are being implemented through partnerships with industry and academia.

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[65] This commercialization decision refers the DOE Hydrogen Program goal for the technology to be sufficiently developed for industry to begin to commercialize fuel cell vehicles and hydrogen refueling infrastructure. See DOE *Hydrogen Posture Plan*, February 2004, page iv.

10. Continued integration and testing of renewable hydrogen production systems is necessary for evaluation of technical and economic barriers.
11. DOE's portfolio includes geographically diverse demonstration projects in 8 states. Research status should approach the outyear targets before large-scale construction of hydrogen production facilities is initiated.

DOE has a viable renewable hydrogen research, development, and demonstration portfolio, but some projects cannot be funded due to Congressionally directed projects. The FY 2006 appropriations impact on project funding could not be assessed for this report. As summarized in the National Academies' hydrogen report, because of the large hydrogen volume potential from solar and wind technologies with near-zero greenhouse gas emissions and greatly reduced use of petroleum (for transportation), multiple technology paths should be pursued.[66]

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[66] *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs*, Committee on Alternatives and Strategies for Future Hydrogen Production and Use, National Research Council and National Academy of Engineering, 2004. Recommendations pp. 120-122.

Appendix

Summary of DOE Solar and Wind Hydrogen Production Projects

Detailed summaries for most projects can be found in the 2005 DOE Hydrogen Program Annual Progress Report (APR) as referenced under the Project Description.

All future funding is subject to appropriations.

* Indicates a Congressionally directed project. Projects labeled as “Deferred” were competitively selected but impacted by Congressionally directed projects.

Prime	Subcontractor Partners	DOE FY05 Obligation	Estimated Total DOE Project Cost	Project Description
Demonstration Projects and Integration Test Sites				
National Renewable Energy Laboratory (Golden, CO) **Sponsor:** EE Hydrogen and Wind Programs	Xcel Energy (Minneapolis, MN) University of North Dakota (Grand Forks, ND) University of Minnesota (Minneapolis/Saint Paul, MN) University of Hawaii (Honolulu, HI) Northern Power Systems (Waitsfield, VT) Proton Energy Systems (Wallingford, CT) Basin Electric (Bismarck, ND)	**$500,000**	**$2,000,000 FY03 to FY07**	Integration of electrolysis with renewable wind and solar power generation systems. Characterization of electrolyzer performance under variable power conditions and development of shared power electronics and controllers packages to reduce cost and optimize system performance. Modeling and integration of electrolysis and fuel cells with direct-coupled wind-based renewable energy applications to improve system efficiency and reduce cost. [APR IV.H.3 p. 340]
Sandia National Laboratory (Albuquerque, NM) **Sponsor:** EE Solar Program	National Renewable Energy Laboratory (Golden, CO)	**$260,000**	**$1,000,000 FY05 to FY07**	Concentrating solar thermal technology research and development for advanced solar electricity and heat generation.
Arizona Public Service (Phoenix, AZ) **Sponsor:** EE Hydrogen Program	GE Global Research, (Niskayuna, NY)	**$500,000**	**$800,000 FY03 to FY06**	Future Power Park to produce hydrogen from solar and wind/electrolysis systems to refuel vehicles and provide distributed power. [APR VIII.B.3 p. 1180]
Hawaii Natural Energy Institute, University of Hawaii, (HNEI) **Sponsor:** EE Hydrogen Program	Hawaiian Electric Company (HECO)	**$520,000**	**$520,000 FY04 to FY06**	Future Power Park to produce hydrogen from wind and geothermal/electrolysis systems to refuel vehicles and provide distributed power. [APR VIII.B.1 p. 1167]
DTE Energy (Detroit, MI) **Sponsor:** EE Hydrogen Program	Daimler Chrysler (Auburn Hills, MI) BP America (Naperville, IL)	**$270,000**	**$2,000,000 FY02 to FY09**	Future Power Park to produce hydrogen from solar and wind/electrolysis and biomass systems to refuel vehicles and provide distributed power. [APR VIII.B.2 p. 1175]
Sunline Services Group (Thousand Palms, CA) **Sponsor:** EE Hydrogen Program	South Coast Air Quality Management District (Diamond Bar, CA)	**$ 0**	**$2,000,000 FY01 to FY06**	Hydrogen fueling facility integrating on-site PV-electrolysis into a public access fueling station. [APR VIII.C.3 p. 1194]
Basin Electric (Bismarck, ND)* **Sponsor:** EE Wind and Hydropower	University of North Dakota (Grand Forks, ND)	**$469,000**	**$996,000 FY04 to FY09**	Dynamically schedule wind-generated electricity via the electric power grid to supply an electrolyzer for hydrogen production, allowing technical and economic assessment of this renewable production pathway.

Prime	Subcontractor Partners	DOE FY05 Obligation	Estimated Total DOE Project Cost	Project Description
Ford Motor Company (Dearborn, MI) **Sponsor:** EE Hydrogen Program	BP America (Naperville, IL)	**$ 0**	**$1,450,000**	PV/Wind Electrolysis for hydrogen vehicle fueling station in Orlando, FL. [APR VIII.A.2 p. 1147]
Electrolysis				
SRI International (Menlo Park, CA) **Sponsor:** EE Hydrogen Program	Institute of High-Temperature Electrochemistry (Russia)	**$200,000**	**$1,800,000 FY05 to FY09**	Reduced electricity cost for through the utilization of high temperature electrolysis. [APR IV.H.9 p. 363]
GE Global Research (Niskayuna, NY) **Sponsor:** EE Hydrogen Program	Northwestern University (Evanston, IL) Functional Coating Technology, LLC (Evanston, IL)	**$25,000**	**$3,200,000 FY05 to FY08**	Reversible solid-oxide fuel-cell/electrolysis system to verify the potential to improve efficiency and hydrogen production cost. [APR IV.H.8 p. 361]
Ceramatec, Inc. (Salt Lake City, UT) **Sponsor:** EE Hydrogen Program	Idaho National Engineering and Environmental Laboratory (Idaho Falls, ID) Hoeganaes Corporation (Cinnaminson, NJ) University of Washington (Seattle, WA)	**$300,000**	**$1,900,000 FY05 to FY08**	Reduced electricity cost for hydrogen production using a novel design for high-temperature solid oxide electrolysis. [APR IV.H.10 p. 367]
Stirling Energy Systems, Inc. (Phoenix, AZ) **Sponsor:** EE Hydrogen Program	University of Alabama in Huntsville (Huntsville, AL) Weizmann Institute of Technology (Israel) Concentrating Technologies, LLC (Owens Cross Roads, AL) University of Massachusetts - Boston (Boston, MA)	**Deferred**	**$3,900,000**	Ultra-high-temperature water splitting for the near-zero-emission production of hydrogen using solar concentrator technology and increased energy efficiency of steam electrolysis through innovative systems approaches.
National Renewable Energy Laboratory **Sponsor:** EE Hydrogen and Solar Programs (FY05 funds from Solar)	Ceramatec, Inc. (Salt Lake City, UT) Solar Systems Pty Ltd (Melbourne, Australia)	**$50,000**	**$150,000 FY05 to FY06**	Feasibility study for integrating concentrating PV with high temperature electrolysis for the co-production of electricity and hydrogen.
Arizona State University (Tempe, AZ) **Sponsor:** EE Hydrogen Program	None	**$170,000**	**$1,200,000 FY05 to FY09**	Novel approach to improve low-temperature electrolysis efficiency through anode surface modification. [APR IV.F.9 p. 276]
Teledyne Energy Systems (Hunt Valley, MD) **Sponsor:** EE Hydrogen Program	Sandia National Laboratory (Albuquerque, NM)	**Deferred**	**$1,500,000**	Novel membrane and electrocatalyst materials for low-temperature alkaline electrolysis to achieve higher efficiencies and better system integration
Teledyne Energy Systems (Hunt Valley, MD) **Sponsor:** EE Hydrogen Program	None	**$300,000**	**$1,600,000 FY04 to FY07**	Advanced high-pressure alkaline electrolysis, targeting part reduction and system design to enable low-cost manufacturing. . [APR IV.H.5 p. 348]
Giner Electrochemical Systems (Newton, MA) **Sponsor:** EE Hydrogen Program	None	**$400,000**	**$1,500,000 FY03 to FY07**	Advanced high-pressure, low-cost PEM electrolysis hydrogen-generation technology. Integration with solar PV technology. [APR IV.H.1 p. 329]

Prime	Subcontractor Partners	DOE FY05 Obligation	Estimated Total DOE Project Cost	Project Description
Proton Energy Systems (Wallingford, CT) **Sponsor:** EE Hydrogen Program	Air Products	**$100,000**	**$1,900,000 FY04 to FY07**	Advanced high-pressure, low-cost PEM electrolysis hydrogen-generation technology. Integrate with wind technology. [APR IV.H.7 p. 357]
GE Global Research* **Sponsor:** EE Hydrogen Program	State University of New York (Albany, New York)	**$ 0**	**$1,500,000 FY04 to FY06**	Novel monolithic stack design to reduce cost and improve manufacturability of large alkaline electrolyzer systems. [APR IV.H.2 p. 334]
University of Toledo (Toledo, OH)* **Sponsor:** EE Hydrogen Program	Bowling Green State University (Bowling Green, OH)	**$125,000**	**$125,000 FY05 to FY07**	Electrolysis system designed for direct integration with PV. [APR IV.F.10 p. 278]
Sandia National Laboratory (Albuquerque, NM) **Sponsor:** EE Hydrogen Program		**$85,000**	**$240,000 FY04 to FY05**	Polymer membranes and higher efficiency electrocatalysts for alkaline electrolysis systems. [APR IV.H.6 p. 353]
University of Nevada – Las Vegas (Las Vegas, NV)* **Sponsor:** EE Hydrogen Program	Proton Energy Systems (Wallingford, CT)	**$1,100,000**	**$3,800,000 FY03 to FY07**	Solar electrolysis fueling station for Las Vegas, NV. [APR IV.H.11 p. 370]
Analytic Power, LLC (Woburn, MA) **Sponsor:** SBIR	None	**$100,000**	**$100,000 FY05 to FY06**	Integrated electrochemical hydrogen compression for water electrolysis. [APR XI.2 p. 1330]
Giner, Inc. (Newton, MA) **Sponsor:** SBIR	None	**$750,000**	**$850,000 FY04 to FY06**	Dimensionally stable high-performance membrane for water electrolysis. [APR XI.6 p. 1332 and XI.9 p. 1334]
Amonix, Inc. (Torrance, CA) **Sponsor:** SBIR	None	**$100,000**	**$700,000 FY04 to FY06**	Integrated, high-efficiency PV-water electrolysis system for hydrogen production. [APR XI.12 p. 1338]
Avalence, LLC (Milford, CT) **Sponsor:** SBIR	None	**$750,000**	**$850,000 FY04 to FY06**	High-efficiency, ultra-high pressure electrolyzer with direct linkage to photovoltaic arrays. [APR XI.13 p. 1339]
EVermont (Waterbury, VT)* **Sponsor:** EE Hydrogen Program	Northern Power Systems (Waitsfield, VT) Proton Energy Systems (Wallingford, CT)	**$ 0**	**$940,000 FY04 to FY07**	Advanced PEM electrolysis fueling station using wind and other renewable electricity sources. [APR IV.H.4 p. 345]
		Photoelectrochemistry		
GE Global Research (Niskayuna, NY) **Sponsor:** EE Hydrogen Program	Caltech (Pasadena, CA)	**$25,000**	**$3,100,000 FY05 to FY09**	Photoelectrochemical water splitting system for the purpose of generating useful quantities of hydrogen via solar energy, including tasks focusing on materials discovery, system design, and prototype construction and demonstration. [APR IV.F.5 p. 268]
University of California - Santa Barbara (Santa Barbara, CA) **Sponsor:** EE Hydrogen Program	National Renewable Energy Laboratory (Golden, CO) GE Global Research (Niskayuna, NY)	**$200,000**	**$900,000 FY05 to FY08**	Combinatorial chemistry methods to discover and optimize an efficient, practical, and economically sustainable material for photoelectrochemical production of bulk hydrogen from water. [APR IV.F.3 p. 256]
MV Systems Inc. (Golden, CO) **Sponsor:** EE Hydrogen Program	University of Hawaii (Honolulu, HI)	**Deferred**	**$3,300,000**	Hybrid photoelectrode device using integrated layers of photoelectrochemical and photovoltaic materials, including parallel efforts in materials research, photoelectrode

Prime	Subcontractor Partners	DOE FY05 Obligation	Estimated Total DOE Project Cost	Project Description
	Intematix Corporation (Moraga, CA) Southwest Research Institute (San Antonio, TX) Duquesne University (Pittsburgh, PA) National Renewable Energy Laboratory (Golden, CO) University of California - Santa Barbara (Santa Barbara, CA)			development, and process scale-up studies. [APR IV.F.8 p. 274]
Midwest Optoelectronics (Toledo, OH) **Sponsor:** EE Hydrogen Program	University of Toledo (Toledo, OH) National Renewable Energy Laboratory (Golden, CO) United Solar Ovonic Corporation (Troy, MI)	**$100,000**	**$2,900,000 FY05 to FY08**	Thin-film silicon-based photoelectrodes including amorphous-silicon-based and microcrystalline-silicon-based photoelectrodes to produce hydrogen from sunlight and water. The approach uses promising multijunction devices with coatings to improve material durability. [APR IV.F.6 p. 270]
National Renewable Energy Laboratory (Golden, CO) **Sponsor:** EE Hydrogen Program	Colorado School of Mines (Golden, CO) University of Colorado (Boulder, CO)	**$800,000**	**$2,800,000 FY05 to FY07**	Experimental and theoretical techniques to perform photoelectrochemical materials research and development and band edge engineering to directly split water and produce hydrogen. [APR IV.F.2 p. 250]
SRI International (Menlo Park, CA) **Sponsor:** EE Hydrogen Program	None	**$250,000**	**$930,000 FY01 to FY06**	High throughput screening approach to discover new photocatalytic materials to generate hydrogen using visible light. [APR IV.F.4 p. 263]
University of Nevada – Las Vegas (Las Vegas, NV)* **Sponsor:** EE Hydrogen Program	Hydrogen Solar, Ltd. (Henderson, NV) Altair Nanotechnologies, Inc. (Reno, NV) National Renewable Energy Laboratory (Golden, CO)	**$2,700,000**	**$3,500,000 FY03 to FY07**	Photovoltaic components coupled to durable photoactive oxide films immersed in suitable electrolytes for direct water splitting. [APR IV.F.1 p. 243]
University of Toledo (Toledo, OH)* **Sponsor:** EE Hydrogen Program	None	**$470,000**	**$470,000 FY05 to FY07**	Thin-film silicon-based photoelectrodes including amorphous-silicon-based and microcrystalline-silicon-based photoelectrodes to produce hydrogen from sunlight and water. The approach uses promising multijunction devices with coatings to improve material durability. [APR IV.F.10 p. 278]
University of Nevada – Las Vegas (Las Vegas, NV)* **Sponsor:** EE Hydrogen Program	University of Hawaii (Honolulu, HI) MV Systems, Inc. (Golden, CO) Intematix, Corp. (Fremont, CA)	**$975,000**	**$1,375,000 FY03 to FY07**	Hybrid photoelectrode" device using integrated layers of photoelectrochemical and photovoltaic materials, including parallel efforts in materials research, photoelectrode development, and process scale-up studies. [APR IV.H.11 p. 370]
Edison Materials Technology Center (Dayton, OH)*	Midwest Optoelectronics (Toledo, OH)	**$200,000**	**$200,000**	Thin-film silicon-based photoelectrodes including amorphous-silicon-based and microcrystalline-silicon-based photoelectrodes to produce hydrogen from sunlight and water. [APR IV.F.11 p. 281]

Prime	Subcontractor Partners	DOE FY05 Obligation	Estimated Total DOE Project Cost	Project Description
Thermochemical Water Splitting Reaction Cycles				
University of Colorado (Boulder, CO) **Sponsor:** EE Hydrogen Program	ETH-Swiss Federal Institute of Technology (Switzerland)	**$100,000**	**$1,100,000 FY05 to FY09**	Manganese oxide cycle for solar-driven thermochemical splitting of water to produce hydrogen. [APR IV.I.2 p. 389]
Science Applications International Corporation (San Diego, CA) **Sponsor:** EE Hydrogen Program	Florida Solar Energy Center (Cocoa, FL) Universidad del Turabo (Puerto Rico) University of Central Florida (Orlando, FL)	**Deferred**	**$4,000,000**	Solar-driven thermochemical water-splitting cycles that can use solar energy in two ways; both to supply high-temperature heat and to utilize a part of the solar spectrum energy directly to catalyze the chemistry.
University of Nevada - Las Vegas (Las Vegas, NV)* **Sponsor:** EE Hydrogen and Solar Programs (Note: FY05 funds from Solar)	General Atomics (San Diego, CA) Sandia National Laboratory (Albuquerque, NM) National Renewable Energy Laboratory (Golden, CO) University of Colorado (Boulder, CO)	**$3,200,000**	**$6,600,000 FY03 to FY07**	Screening of potential solar-driven high-temperature water- splitting cycles; down-selection to the most promising ones; and research, development, and demonstration of at least one cycle that meets the hydrogen production cost goal of $2-$3/GGE of hydrogen. [APR IV.I.1 p. 377]
Biological Hydrogen Production				
University of California - Berkeley (Berkeley, CA) **Sponsor:** EE Hydrogen Program	None	**$200,000**	**$1,200,000 FY05 to FY09**	Increased efficiency of light absorption by microorganisms to address the technical barrier of low light utilization efficiency in photobiological hydrogen production due to a large photosystem chlorophyll antenna size. [APR IV.E.1 p. 211]
J. Craig Venter Institute (Rockville, MD) **Sponsor:** EE Hydrogen Program	National Renewable Energy Laboratory (Golden, CO)	**$350,000**	**$2,880,000 FY05 to FY08**	Combining the properties of two microorganisms – cyanobacteria and photosynthetic bacteria – to develop a novel, hybrid microbe with two highly desirable traits not found together in nature: the ability to produce hydrogen in the presence of oxygen, using water as the feedstock. [APR IV.E.6 p. 241]
Oak Ridge National Laboratory (Oak Ridge, TN) **Sponsor:** EE Hydrogen Program	None	**$600,000**	**$700,000 FY04 to FY06**	Increased rate of algal hydrogen production (water splitting) by designing a proton channel to reduce the proton gradient during hydrogen production, the physiological obstacles that limit the absorbed light energy to hydrogen efficiency will be minimized. [APR IV.E.3 p. 225]
National Renewable Energy Laboratory (Golden, CO) **Sponsor:** EE Hydrogen Program	Beckman Institute, University of Illinois (Urbana, IL) CEA/CNRS, Grenoble, France	**$900,000**	**$3,200,000 FY05 to FY07**	Research on surmounting the oxygen sensitivity of the enzyme responsible for biological hydrogen photoproduction through increased understanding of biochemical machinery necessary to efficiently

Prime	Subcontractor Partners	DOE FY05 Obligation	Estimated Total DOE Project Cost	Project Description
	University of Minnesota (Minneapolis/Saint Paul, MN)			photoproduce hydrogen from water using a biological catalyst. [APR IV.E.2 p. 216]
Advanced BioNutrition Corporation (Columbia, MD) **Sponsor:** EE Hydrogen Program	Brooklyn College of the City University of New York (Brooklyn, NY)	**Deferred**	**$4,300,000**	Novel two-stage, indirect, biophotolytic hydrogen production process in which stored algal polyglucose is converted to hydrogen in a dark fermentation reaction.
	Clemson University (Clemson, SC)			
	Savannah River Technology Center (Aiken, SC)			
	SeaAg, Inc. (Vero Beach, FL)			
	University of Hawaii (Honolulu, HI)			
Montana State University (Bozeman, MT) **Sponsor:** EE Hydrogen Program	Pleotint, LLC (West Olive, MI)	**Deferred**	**$1,200,000**	Hydrogen production using visible light and simple organic acids (such as acetate - vinegar). [APR IV.F.7 p. 272]
Basic Research for Solar Hydrogen Production				
Colorado State University (Fort Collins, CO) **Sponsor:** Science		**$180,000**	**$590,000 FY05 to FY07**	A combinatorial approach to identify new semiconducting mixed oxides for photoelectrochemical water splitting under visible light illumination. Novel idea to deposit metal oxide precursors by ink jet printing on a conductive glass substrate, pyrolysis to produce thin films, and visible wavelength scan to detect photocurrent upon immersion of the films in aqueous electrolyte. [APR II p. 13]
California Institute of Technology (Pasadena, CA) **Sponsor:** Science		**$225,000**	**$690,000 FY05 to FY07**	Combinatorial screening of metal sulfides for photocathodes and metal oxides for photoanodes, using a modified ink jet printer. Development of membrane-supported geometrically organized photocatalyst structures for production of hydrogen and oxygen on either sides of a membrane. [APR II p. 13]
University of Arizona (Tucson, AZ) **Sponsor:** Science		**$220,000**	**$670,000 FY05 to FY07**	Nanohybrid assemblies for photocatalytic hydrogen production based on wired semiconductor nanoparticles or dye-modified dendrimers embedded in microporous silica films. [APR II p. 13]
University of California, Santa Cruz (Santa Cruz, CA) **Sponsor:** Science	University of Georgia (Athens, Georgia)	**$150,000**	**$450,000 FY05 to FY07**	Photoelectrochemical cell for hydrogen generation based on TiO2 nanowires for photoanode and Pt wires for cathode. he external bias provided by a novel photovoltaic cell based on Si nanowire arrays or sensitized TiO2. Novelty is fabrication of nanowires by GLAD (glancing angle deposition). [APR II p. 13]

Prime	Subcontractor Partners	DOE FY05 Obligation	Estimated Total DOE Project Cost	Project Description
Pennsylvania State University (University Park, PA) **Sponsor:** Science		**$135,000**	**$415,000 FY05 to FY07**	Tandem photovoltaic cell comprised of a dye-sensitized solar cell with greatest efficiency in the visible and single crystal Si cell that operates most efficiently in the near infrared. The iodine couple is replaced in the dye cell. Photovoltaic-driven water electrolysis. [APR II p. 13]
Purdue University (West Lafayette, IN) **Sponsor:** Science		**$130,000**	**$370,000 FY05 to FY07**	Materials synthesis via electrodeposition methods of polycrystalline electrodes for photoelectrochemical cells. Focus on Cu2O-WO3 composites. [APR II p. 13]
Pennsylvania State University (University Park, PA) **Sponsor:** Science		**$245,000**	**$695,000 FY05 to FY07**	Novel Si and CdSe nanowires and nanoarrays for photoelectrochemical water splitting. [APR II p. 13]
University of Washington (Seattle, WA) **Sponsor:** Science		**$120,000**	**$365,000 FY05 to FY07**	Theoretical studies on dye-sensitized solar cells, quantum dots for generation of multiple carriers, and carbon nanotube electronic properties. Relevant to photovoltaic-driven electrolysis of water. [APR II p. 13]
Nanoptek Corporation (Maynard, MA) **Sponsor:** Science		**$100,000**	**$300,000 FY05 to FY07**	Research on the energy gap redshift in TiO2 produced by alteration of the lattice parameters. The TiO2 electrodes optimized for photoelectrochemical water splitting. [APR II p. 13]
Virginia Polytechnic Institute and State University (Blacksburg, VA) **Sponsor:** Science		**$135,000**	**$395,000 FY05 to FY07**	Mechanistic photochemical studies on trinuclear, rhodium-centered mixed-metal complexes for photocatalytic water splitting. [APR II p. 13]
Brookhaven National Laboratory (Upton, NY) **Sponsor:** Science	New York University (New York, NY)	**$800,000**	**$2,450,000 FY05 to FY07**	Photoelectrochemical water splitting by visible light. Studies on bandgap-narrowed semiconductor photoanodes and transition metal catalysts for water oxidation at the anode surface. [APR II p. 13]
Pacific Northwest National Laboratory (Richland, WA) **Sponsor:** Science		**$550,000**	**$1,750,000 FY05 to FY07**	Photocatalytic water splitting on anion-doped single crystal surfaces. Fundamental surface science approach to anion doping in TiO2 and Pt/TiO2. [APR II p. 13]
National Renewable Energy Laboratory (Golden, CO) **Sponsor:** Science	University of Colorado (Boulder, CO)	**$350,000**	**$1,350,000 FY05 to FY07**	A novel approach to solar water splitting in which two electron-hole pairs are created per absorbed photon. The doubling occurs in unique chromophores that can undergo singlet fission or in semiconductor quantum dots[APR II p. 13]
Basic Research for Bio-Inspired Hydrogen Production				
University of Washington (Seattle, WA) **Sponsor:** Science		**$670,000**	**$1,030,000 FY05 to FY07**	Combination of hypothesis-driven and discovery-based experimental plan to use energy from an electrochemical gradient to drive hydrogen production. [APR II p. 13]
University of Georgia (Athens, Georgia) **Sponsor:** Science		**$250,000**	**$766,000 FY05 to FY07**	Design a minimal hydrogenase from components of different microbial systems, and develop a robust heterologous expression system for its production. Then perform high throughput screening and assembly of stable and functional membrane-vesicle hybrid hydrogen. [APR II p. 13]

Prime	Subcontractor Partners	DOE FY05 Obligation	Estimated Total DOE Project Cost	Project Description
Pennsylvania State University (University Park, PA) **Sponsor:** Science		**$175,000**	**$525,000 FY05 to FY07**	A Hybrid Biological/Organic Half-cell for Generating Dihydrogen. [APR II p. 13]
University of Pennsylvania (Philadelphia, PA) **Sponsor:** Science		**$200,000**	**$600,000 FY05 to FY07**	Modular Designed Protein Constructions for Solar Generated H2 from Water. [APR II p. 13]
University of Oklahoma (Norman, OK) **Sponsor:** Science		**$0**	**$628,000 FY06 to FY08**	Characteristics of an H2 Producing Biological System Operating at 1 nM H2 Concentration. [APR II p. 13]
National Renewable Energy Laboratory (Golden, CO) **Sponsor:** Science		**$800,000**	**$2,428,000 FY05 to FY07**	Structural, Functional, and Integration Studies of Biocatalysts for Development of Solar Driven, Bio-Hybrid, H2-Production Systems. [APR II p. 13]