II.0 Hydrogen Production Sub-Program Overview

INTRODUCTION

The Hydrogen Production sub-program supports research and development (R&D) of technologies that will enable the long-term viability of hydrogen as an energy carrier for a diverse range of end-use applications, including transportation (e.g., specialty vehicles, cars, trucks, and buses), stationary power (e.g., backup power and combined heat and power systems), and portable power. A portfolio of hydrogen production technology pathways utilizing a variety of renewable energy sources and renewable feedstocks is being developed under this sub-program.

Multiple DOE offices are engaged in R&D relevant to hydrogen production, including the following.

- The Fuel Cell Technologies Office (FCTO), within the Office of Energy Efficiency and Renewable Energy (EERE), is developing technologies for distributed and centralized renewable production of hydrogen, including conversion of biomass-derived feedstocks, advanced water splitting (including high temperature/pressure operations and novel catalyst/membranes), direct solar water splitting (including thermochemical and photoelectrochemical [PEC] processes), and biological processes.
- The Office of Fossil Energy (FE) is advancing the technologies needed to produce hydrogen from fossil fuel resources, including co-production of hydrogen and electricity. FE is also developing technologies for carbon capture, utilization, and storage, which could ultimately enable reduced-emissions pathways for hydrogen production from fossil resources.
- The Office of Science's Basic Energy Sciences (BES) program conducts research to expand the fundamental understanding of processes and mechanisms relevant to hydrogen production, including biological and biomimetic hydrogen production, photoelectrochemical water splitting, catalysis, and membranes for gas separation.
- The Office of Nuclear Energy (NE) is currently collaborating with EERE on a study of nuclear-renewable hybrid energy systems. Many of the systems being evaluated by this study use hydrogen as a form of energy storage or as an input to industrial processes.

GOAL

The goal of the Hydrogen Production sub-program is to develop low cost, highly efficient hydrogen production technologies that utilize diverse domestic sources of energy, including renewable resources (EERE), coal with sequestration (FE), and nuclear power (NE).

OBJECTIVES

The objective of the Hydrogen Production sub-program is to reduce the cost of hydrogen dispensed at the pump to a cost that is competitive on a cents-per-mile basis with fuels used in competing vehicle technologies. Based on current analysis, this translates to a hydrogen cost target of <$4/kg hydrogen (produced, delivered, and dispensed, but untaxed) by 2020[1], with <$2/kg apportioned for production only[2]. Technologies are being developed to achieve this goal in timeframes appropriate to their current stages of development.

The objectives of FE's efforts in hydrogen production are documented in the *Hydrogen from Coal Program Research, Development and Demonstration Plan* (September 2010)[3]. They include proving the feasibility of a near-zero emissions, high efficiency plant that will produce both hydrogen and electricity from coal and reduce the cost of hydrogen from coal by 25% compared with current technology by 2016. The objectives of NE's collaborative efforts with FCTO are documented in the report: *Rethinking the Future Grid: Integrated Nuclear Renewable Energy Systems*[4].

[1] *Hydrogen Threshold Cost Calculation*, Program Record (Office of Fuel Cell Technologies) 11007, U.S. Department of Energy, 2012, http://www.hydrogen.energy.gov/pdfs/11007_h2_threshold_costs.pdf

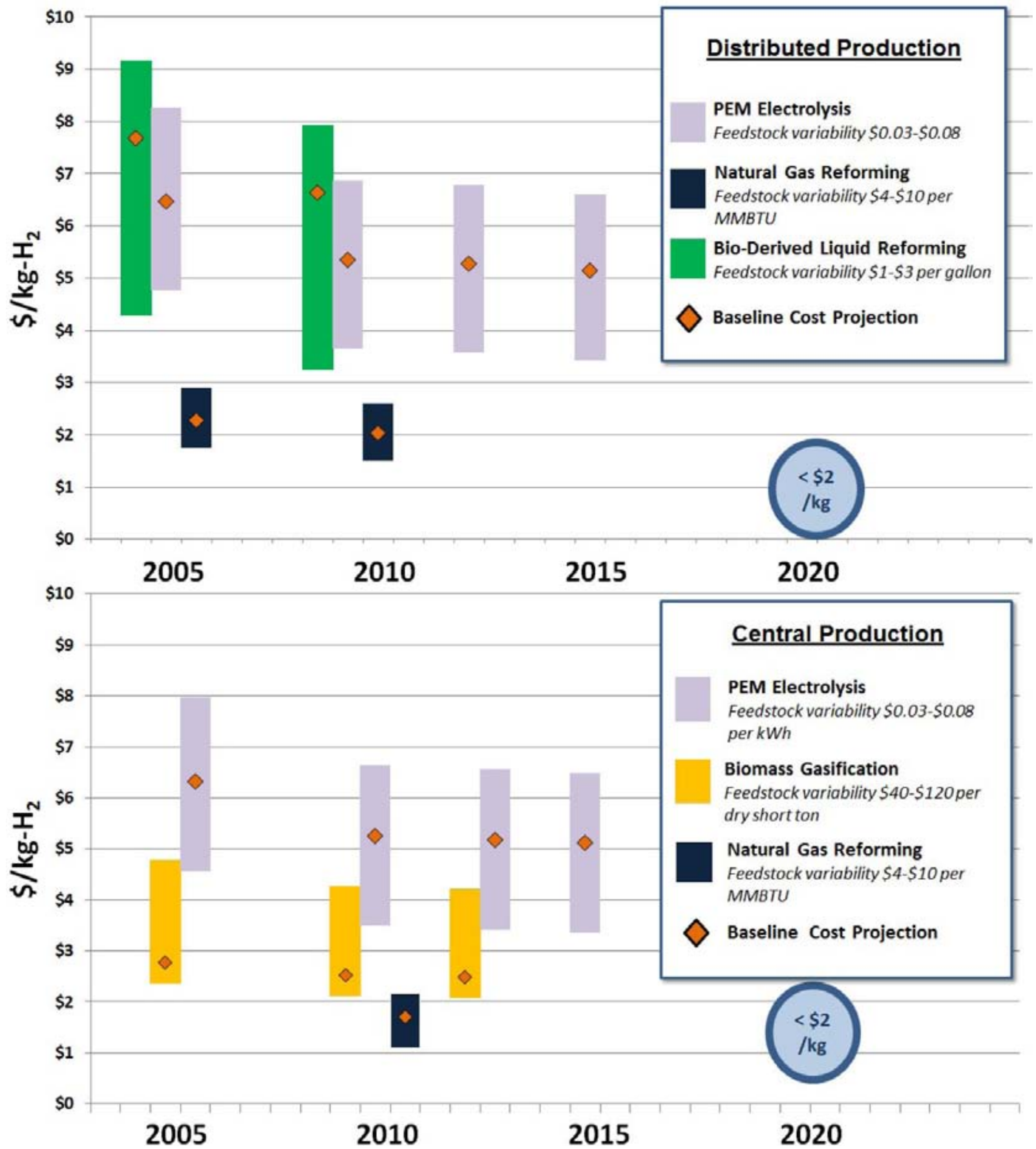
[2] *Hydrogen Production and Delivery Cost Apportionment*, Program Record (Office of Fuel Cell Technologies) 12001, U.S. Department of Energy, 2012, http://hydrogen.energy.gov/pdfs/12001_h2_pd_cost_apportionment.pdf

[3] *Hydrogen from Coal Program Research Development and Demonstration Plan*, Office of Fossil Energy, U.S. Department of Energy, September 2010, http://fossil.energy.gov/programs/fuels/hydrogen/2010_Draft_H2fromCoal_RDD_final.pdf

[4] *Rethinking the Future Grid: Integrated Nuclear Renewable Energy Systems*, National Renewable Energy Laboratory, December 2014, http://www.nrel.gov/docs/fy15osti/63207.pdf

FISCAL YEAR (FY) 2015 TECHNOLOGY STATUS AND PROGRESS

Recent and current status for the high-volume projected costs of hydrogen production for several of the near- to mid-term production pathways is shown in Figure 1. The figure highlights the reduction in costs in recent years resulting from R&D. It is seen that natural gas reforming is the only technology meeting the FCTO cost target of <$2/kg. Ongoing R&D is exploring ways to accelerate development and reduce cost in all available hydrogen production technology pathways, including the mid- to long-term renewable pathways.



PEM – Polymer electrolyte membrane

FIGURE 1. Range of hydrogen production costs, untaxed, for near- to mid-term distributed and centralized pathways. The high end of each bar represents a pathway-specific high feedstock cost as well as an escalation of capital cost, while the low end reflects a low feedstock cost and no capital escalation. Bars for different years in the same pathway represent improvements in the costs of the specific pathway, based on specific reference data for the appropriate year and pathway. Detailed information is included in the DOE Hydrogen and Fuel Cells Program Record #14005[5].

[5] DOE Hydrogen and Fuel Cells Program Record #14005 Hydrogen Production Status 2006-2013, under development

In FY 2015, significant progress was made by the Hydrogen Production sub-program on several important fronts. Highlights include the following.

- The second H-Prize competition, H2 Refuel, was launched in October 2014. This $1 million competition challenges America's innovators to deploy an on-site hydrogen generation system to fuel hydrogen-powered vehicles. The system may use electricity or natural gas and can be sited in homes, community centers, small businesses, or similar locations.
- The H2A (Hydrogen Analysis) Tool was enhanced to include an updated economic basis and easy-to-read results containing tornado and waterfall plots.
- A joint workshop was held by FCTO and the Bioenergy Technologies Office (BETO) in March 2015, titled *Hydrogen, Hydrocarbons, and Bioproduct Precursors from Wastewaters*. The workshop presentations have been posted online[6], and a workshop report will be posted in FY 2016. A Request for Information to solicit public input will follow.

Detailed FY 2015 progress in the Hydrogen Production sub-program is described below.

New Project Selections

In FY 2015, an Incubator funding opportunity announcement (FOA) was released to support R&D efforts to address critical challenges and barriers to hydrogen production and delivery technology development, and specifically the long-term goal of hydrogen production at <$2/kg hydrogen. Innovative materials, processes, and systems are needed to establish the technical and cost feasibility for renewable and low carbon hydrogen production and delivery. Specifically, the Incubator FOA sought research on game-changing technologies that could reach FCTO targets but were under-represented in the Program's Multi-Year Research, Development, and Demonstration Plan targets and/or research portfolio. The four selected projects are as follow.

- Proton OnSite, Wallingford, Connecticut, will advance alkaline-exchange-membrane-based electrolysis technology by developing durable and efficient precious group metal (PGM)-free electrolysis cells.
- Versa Power Systems, Littleton, Colorado, will develop hydrogen production technologies using high temperature solid oxide electrolysis capable of operating at high current densities (i.e., high hydrogen production rates) and high efficiencies.
- University of California, Irvine will develop a novel photocatalyst particle-based slurry reactor with the potential for low cost renewable hydrogen production via solar water splitting.
- Virginia Polytechnic Institute and State University, Blacksburg, Virginia, will develop a cell-free biological hydrogen production technology based on an in vitro synthetic biosystem composed of numerous thermoenzymes and biomimetic coenzymes.

Four *solar water splitting* projects awarded in FY 2014 under the National Science Foundation (NSF)/FCTO joint solicitation NSF 14-511: NSF/DOE Partnership on Advanced Frontiers in Renewable Hydrogen Fuel Production, were initiated. The four projects are listed below.

- The University of Toledo, Toledo, Ohio, initiated the project titled: New Metal Oxides for Efficient Hydrogen Production Via Solar Water Splitting.
- Stanford University, Stanford, California, initiated the project titled: Engineering Surfaces, Interfaces, and Bulk Materials for Unassisted Solar Photoelectrochemical (PEC) Water Splitting.
- The University of Colorado (CU) at Boulder, Boulder, Colorado, initiated the project titled: Accelerated Discovery of Advanced RedOx Materials for Solar Thermal Water Splitting to Produce Renewable Hydrogen.
- Rutgers University, New Brunswick, New Jersey, initiated the project titled: Tunable Semiconductor/Catalyst Interfaces for Efficient Solar Water Splitting.

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[6] *Hydrogen, Hydrocarbons, and Bioproduct Precursors from Wastewaters*, Joint workshop of DOE's FCTO and BETO, March 2015, http://energy.gov/eere/fuelcells/hydrogen-hydrocarbons-and-bioproduct-precursors-wastewaters-workshop

H2A Technoeconomic Case Studies

Industry-vetted case studies of hydrogen production costs via solid oxide electrolyzer cells (SOEC) and fermentation were completed using the H2A v3 tool, and these studies are being made publically available on the DOE website. In these studies, representative SOEC and fermentation systems were modeled based on input from several key industry collaborators with commercial experience. Both technologies were analyzed as centralized production facilities with a capacity of 50,000 kg/d, and both were evaluated at two technology years (current: 2015 and future: 2025). The technoeconomic case study process included soliciting relevant, detailed information from the companies followed by synthesizing and amalgamating the data into base parameters and sensitivity limits that were vetted by the industry collaborators. Results included the following.

- The results of the SOEC case studies show hydrogen production costs (at high volume, untaxed) of $4.21/kg and $3.68/kg for current and future cases, respectively. Key cost drivers were identified and quantified, including electricity cost, electrical efficiency, and capital cost.
- The results of the fermentation case studies show hydrogen production costs (at high volume, untaxed) of >$100/kg for the current case, but reduced to $4.62/kg for the future case. The cost of the current case is dominated by utility heating cost. The heat requirement of the future case is projected to be offset by using heat from burning lignin in the system.

(Strategic Analysis, Inc., National Renewable Energy Laboratory [NREL], Argonne National Laboratory)

Electrolytic Hydrogen Production

The major emphases of the electrolysis projects were on cost reduction and efficiency improvement through leveraging catalyst development. Work on alkaline membrane electrolysis is showing promise to deliver electrolyzer systems with very low PGM loading. Additional work is needed to reduce electrolyzer system costs by reducing balance of plant losses, such as dryer losses. Technical progress included the following.

- A large active area stack electrolyzer test bed (sub-megawatt scale) and dryer skid were installed to allow independent performance testing. Preliminary variable-flow drying demonstrations suggest that over 1,000 kg H_2/yr would be saved, compared to traditional drying methods, by coupling the electrolyzer stack with 1 MW wind electricity. (NREL)
- High pressure electrolysis with stable performance was demonstrated for 1,000 h at 95°C and for 500 h at 95°C and 1,000 psi in advanced PEM electrolysis membranes. (Giner, Inc.)
- Three different types of low PGM loaded (<0.5 mg/cm^2) anode catalysts were developed that have comparable performance to Giner's standard anode (4 mg PGM/cm^2). (Giner, Inc.)
- A manufacturable ultra-low PGM loaded cathode was developed with greater than 500 h durability. Core shell catalysts were demonstrated to have activity advantages by enabling lower loadings at equivalent performance. (Proton OnSite)

PEC Hydrogen Production

The main focus of projects in this area was on using state-of-the-art theory, synthesis, and characterization tools to develop viable PEC material systems and prototypes with improved efficiency and durability. Technical progress included the following.

- Greater than 460 hours of stabilized device operations were demonstrated for III-V semiconductor PEC tandem devices using an NREL-developed ion bombardment surface passivation process (patent pending). This result represents an important step forward toward demonstration of stabilized solar-to-hydrogen conversion efficiencies >20% using PEC devices. (NREL)
- Photoactive $CuInGaS_2$ with controlled composition and tunable bandgap in the 1.5–2.4 eV range was successfully fabricated. Initial demonstration of chalcopyrite surface protection with MoS_2 was also demonstrated. (University of Hawaii)

Thermochemical Bio-Feedstock Conversion Production

The technical focus of projects in this area was on using thermochemical methods to produce hydrogen from biomass-derived feedstocks. Technical progress included the following.

- Cell performances with >30% increase in hydrogen production and >20% increase in hydrogen purity were achieved through implementation of an electrolysis step (compared to the base process without the electrolysis step). (FuelCell Energy, Inc.)
- Two promising carbon dioxide (CO_2) sorbents were identified for respective low-temperature and high-temperature sorption, and two promising low-temperature reforming catalysts were identified through modeling and bio-oil reforming tests. (Pacific Northwest National Laboratory)

Biological Hydrogen Production

The broad focus of the projects in the biological hydrogen production portfolio was to address key barriers such as oxygen sensitivity and feedstock utilization using molecular biology and genetic engineering techniques along with improved systems engineering. Technical progress included the following.

- Hydrogen production at an average rate of 757 mL H_2/L/d from de-acetylated and mechanically refined feedstock was demonstrated. (NREL)
- Roles of the two different sets of hydrogenase maturation genes, *hyp1* and *hyp2*, were confirmed. Also, a *Synechocystis* strain expressing the non-native CBS hydrogenase and maturation proteins was developed. (NREL)

Solar Thermochemical Hydrogen (STCH) Production

Efforts in these projects were directed toward performance characterization of water splitting by novel, non-volatile metal-oxide-based reaction materials and development of new reactor concepts to optimize efficiency of the reaction cycles. Technical progress included the following.

- A prototype 3 kW cascading pressure reactor/receiver was designed, and the approach to material discovery and engineering of thermochemical properties was extended such that greater than 50 new compounds have been developed. (Sandia National Laboratories)
- A solar hybrid sulphur process was designed that uses a bayonet acid decomposer and thermal energy storage, including an Aspen Plus® flowsheet and performance evaluation. (Savannah River National Laboratory)
- A flowing particle reactor design was completed, including Aspen Plus® process modeling. More than 2 g of hercynite active material was synthesized by spray drying. This material was characterized for composition, particle size, and surface area. (CU Boulder)
- 1,045 possible binary perovskites were screened, of which 199 materials show potential for use in STCH. (CU Boulder)

BUDGET

The FY 2015 appropriation for the Hydrogen Production and Delivery sub-programs was $19.6 million. Funding was distributed approximately evenly between Production and Delivery, with Production allocated $9.8 million. This split reflects the priority to maintain a balanced R&D portfolio focused both on near- and longer-term technology options. The request for Production and Delivery in FY 2016 is $23.6 million, with $12 million slated for Production. The estimated budget breakdown for Production funding in FY 2015 and FY 2016 is shown in Figure 2.

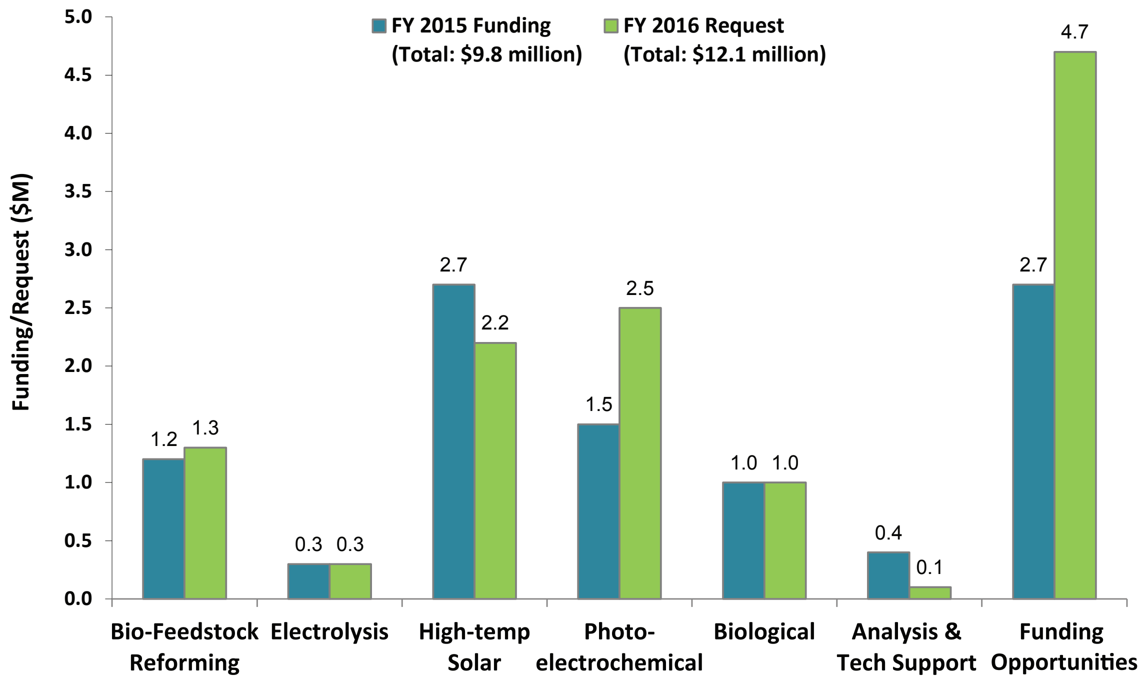

FIGURE 2. Hydrogen Production R&D Funding. Subject to appropriations, project go/no-go decisions, and competitive selections. Exact amounts will be determined based on research and development progress in each area and the relative merit and applicability of projects competitively selected through planned funding opportunity announcements.

With the near-term emphasis on forecourt stations and infrastructure in the Delivery portfolio, and with natural gas reforming a viable option for supplying near-term hydrogen demands, the Production R&D portfolio has increasingly focused on mid- to longer-term, renewable pathways such as advanced conversion of bio-derived feedstocks, advanced water-splitting, direct water-splitting through PEC, and solar-thermochemical processes. The R&D emphasis on a balanced portfolio of long-term and nearer-term renewable technologies is expected to continue into FY 2016. Projects selected in a FY 2014 FOA in areas of bio-derived feedstock conversion and photoelectrochemical and solar thermochemical water splitting will continue, supplemented by the four joint NSF/FCTO projects in solar water splitting and the five new Incubator projects. In addition, a new laboratory consortium on renewable hydrogen production will be initiated on advanced water-splitting technologies, including enhancement of core capabilities in materials-device and system-level development for advancing technology readiness level (TRL) in technologies including photoelectrochemical and solar-thermochemical water splitting.

FY 2016 PLANS

General Hydrogen Production program plans for FY 2016 include the following.

- Continue to demonstrate substantial progress in the six Production projects selected in the FY 2014 FOA; demonstrate initial progress in the five new projects selected under the 2015 Incubator FOA and in the four advanced water-splitting projects selected under the FY 2014 NSF/FCTO joint solicitation.
- Continue emphasis on materials durability, production efficiency, and process optimization for all pathways, and develop and refine materials characterization protocols and performance metrics for early development technologies.
- Assess the sustainability of incumbent hydrogen production technologies (e.g., steam methane reforming and carbon sequestration), as well as renewable alternatives. Baselines will be developed through collaboration with industry and reviews of existing literature, including H2A case studies and life-cycle analyses.
- Continue collaboration with the NSF and BES and Advanced Research Projects Agency-Energy.

- Initiate the new laboratory consortium on advanced water-splitting technologies, including enhancement of core capabilities in materials-device and system-level development for advancing TRL in technologies including PEC and solar-thermochemical water splitting.

Important pathway-specific milestones planned for FY 2016 in the Hydrogen Production sub-program projects include the following.

- Demonstrate >500 hours of hydrogen production from bio-derived liquids with in situ CO_2 capture and >90% pure H_2.
- Design a megawatt-scale STCH production plant for 100,000 kg/d, and show, through modeled performance analysis, the capability to meet the $2/kg cost target.
- Develop photovoltaic-grade wide band gap thin film absorbers with photoelectrochemical solar photocurrent densities $\geq$13 mA/cm^2 to enable 16% solar-to-hydrogen conversion efficiency.

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