II.0 Hydrogen Production Program Overview

INTRODUCTION

The Hydrogen Production 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 (e.g., auxiliary power units). A portfolio of hydrogen production technology pathways utilizing a variety of renewable energy sources and renewable feedstocks is being developed under this program.

Multiple DOE offices are engaged in R&D relevant to hydrogen production:

- The Fuel Cell Technologies Office (FCTO), within the Office of Energy Efficiency and Renewable Energy (EERE), is developing technologies that include conversion of biomass-derived feedstocks, advanced water splitting (including high temperature/pressure operations and novel catalysts/membranes), direct solar water splitting (including thermochemical and photoelectrochemical processes), and biological processes.
- 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 through photoelectrochemical water splitting, catalysis, membranes for gas separation, and biological and biomimetic processes.
- The Office of Nuclear Energy (NE) is currently collaborating with EERE on a study of nuclear–renewable hybrid energy systems, called Hydrogen at Scale (H2@Scale). Consistent with the vision of H2@Scale, many of the systems being evaluated by this study use hydrogen production as a form of energy storage or as an input to industrial 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 and steam methane reformation. FE also continues to develop technologies for carbon capture, utilization, and storage, which could ultimately enable reduced emissions pathways for hydrogen production from fossil resources.

GOAL

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

OBJECTIVES

The objective of the Hydrogen Production program is to reduce the cost of renewable hydrogen dispensed at the pump to a cost that is competitive on a cents-per-mile basis with competing vehicle technologies. Based on current analysis, this translates to a hydrogen cost target of <$4/kg H_2 (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.

FISCAL YEAR (FY) 2016 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 are shown in Figure 1 below. The figure highlights the reduction in costs in recent years resulting from continued R&D. Natural gas reforming (without carbon capture) already meets the FCTO cost target of <$2/kg, but ongoing R&D is needed to accelerate development and reduce cost in all the renewable hydrogen production technology pathways for large-scale production in the mid to long terms.

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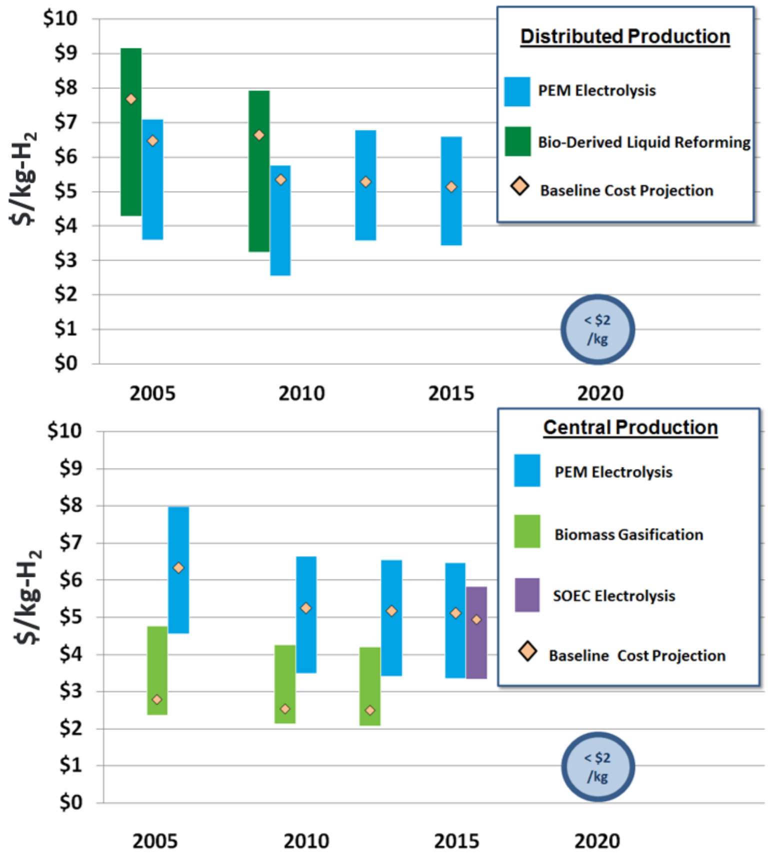
[1] DOE Hydrogen and Fuel Cells Program Record #11007, Hydrogen Threshold Cost Calculation, 2012, http://www.hydrogen.energy.gov/pdfs/11007_h2_threshold_costs.pdf

[2] DOE Hydrogen and Fuel Cells Program Record #12001, Hydrogen Production and Delivery Cost Apportionment, 2012, http://hydrogen.energy.gov/pdfs/12001_h2_pd_cost_apportionment.pdf



PEM – polymer electrolyte membrane; SOEC – solid oxide electrolysis cell

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 end on 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 Records #14005[3] and #16014[4].

Program-Level Accomplishments

In FY 2016, significant progress was made by the Hydrogen Production program on several important fronts.

- A workshop was held in April 2016 to engage stakeholders in advanced water splitting materials and share information on electrochemical, photoelectrochemical (PEC), and solar thermochemical pathways for producing hydrogen using renewable energy sources. A workshop web page was launched, including the workshop presentation materials.
- The HydroGEN advanced water splitting materials consortium was launched as part of DOE's Energy Materials Network to accelerate materials discovery and development of critical to advanced water splitting technologies for renewable hydrogen production. HydroGEN has begun work to identify technical and analytical resources available at the national laboratories to support state-of-the-art renewable hydrogen production research. HydroGEN is also developing a website to provide public information on the expertise and capabilities that will be available through collaboration with the HydroGEN consortium.

[3] DOE Hydrogen and Fuel Cells Program Record #14005, Hydrogen Production Status 2006-2013, 2014, https://www.hydrogen.energy.gov/pdfs/14005_hydrogen_production_status_2006-2013.pdf
[4] DOE Hydrogen and Fuel Cells Program Record #16014, Hydrogen Production Cost from Solid Oxide Electrolysis , 2016, https://www.hydrogen.energy.gov/pdfs/16014_h2_production_cost_solid_oxide_electrolysis.pdf

- Several FCTO-funded projects made significant achievements, including advances in low-carbon hydrogen production from bio-feedstocks; progress in advanced electrolysis technologies for alkaline exchange membrane and solid oxide-based electrolyzers; and progress on PEC and solar-thermochemical hydrogen (STCH) production goals as well as innovative materials research to advance PEC and STCH pathways (all described in further detail below).

Project-Level Accomplishments

During FY 2016, progress was made by existing projects in several key areas.

New Project Selections

In FY 2016, FCTO released one Funding Opportunity Announcement (FOA) 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 H_2. 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 FOA sought research on materials improvements for increased durability and efficiency in high temperature electrolysis.

Three electrolysis projects were selected in FY 2016 under the Production portfolio and will begin work in early FY 2017:

- Giner Inc., Newton, Massachusetts, will work to develop high-temperature molten hydroxide alkaline water electrolyzers with improved electrical efficiency at a reduced cost.
- Ceramatec Inc., Salt Lake City, Utah, will aim to improve the performance of durable materials for high-temperature water splitting by developing a novel stack technology.
- FuelCell Energy, Inc., Danbury, Connecticut, will demonstrate a highly efficient solid oxide electrolysis cell (SOEC) system with a goal of producing hydrogen at a cost of \$2/kg.

Additionally, one analysis project was awarded in FY 2016 and will begin work in FY 2017:

- Strategic Analysis Inc., Arlington, Virginia, will perform detailed cost analyses for hydrogen production and delivery technologies to assess the potential of each pathway to meet the DOE hydrogen cost goal of <\$4/kg H_2 by 2020 and identify critical barriers for the given technologies.

Hydrogen Production Pathway Analysis

Case studies of hydrogen production costs for both a monolithic piston-type bio-oil reformation reactor and a reformer–electrolyzer–purifier system are nearing completion using the H2A v3 tool, and selected results from these studies will be made publically available. In these studies, industrial-scale systems were modeled based on input from the key researchers involved in the projects developing these technologies. The technoeconomic case study process included soliciting relevant, detailed information from research institutions followed by synthesizing and amalgamating the data into base cases with sensitivity analysis using baseline parameters and sensitivity limits that were vetted by the industry collaborators. (Strategic Analysis, Inc., National Renewable Energy Laboratory [NREL], Argonne National Laboratory).

Electrolytic Hydrogen Production

The major emphases of the electrolysis projects were on cost and greenhouse gas emission reduction by improving cell and stack efficiency and durability. Technical progress included the following:

- Developed a new solid oxide electrolysis cell and stack capable of ultra-high-current operation. Demonstrated an SOEC short stack operating at a current density of 3 A/cm^2 at less than 1.6 V and developed the preliminary ultra-high-current-density SOEC system conceptual design. (Versa Power Systems)
- Operated an alkaline exchange membrane (AEM)-based electrolysis cell with precious-group-metal-free anode and cathode at less than 2 V at 500 mA/cm^2. This is one of the first known demonstrations of an AEM electrolyzer membrane electrode assembly operating with no precious group metal content. (Proton Onsite)

Photoelectrochemical 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:

- A world-record efficiency of greater than 16% was demonstrated for III-V semiconductor PEC tandem devices. This was enabled through the use of an inverted metamorphic multijunction, which dramatically reduced voltage losses at interfaces. This result represents an important step forward toward demonstration of 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. Photocurrents of over 10 mA/cm^2 were achieved, and new protective coatings were applied to increase durability. (University of Hawaii)
- A model developed for particle-based, tandem PEC reactors showed that a 1% solar-to-hydrogen efficiency is possible for over 200 days without mechanical agitation. This accomplishment, combined with technoeconomic analysis, provides an important foundation for experimental work on particle-based PEC devices. (University of California, Irvine)

Thermochemical Bio-Feedstock Conversion Production

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

- Using commercial molten carbonate fuel cell components in electrolyzer mode, reformer–electrolyzer–purifier technology was successfully demonstrated at the 100 kg H_2/d scale using natural gas as the representative feedstock. Cell performance with greater than 30% increase in hydrogen production and greater than 20% increase in hydrogen purity was achieved through implementation of the electrolysis step (compared to the base process without the electrolysis step). (FuelCell Energy, Inc.)
- An active and novel catalyst system for the steam reforming of bio-oil with periodic regeneration by combustion was demonstrated, and a new flow distributor design that successfully distributes bio-oil evenly into the monolith catalyst channels under reaction conditions was developed. (Pacific Northwest National Laboratory)

Biological Hydrogen Production

The focus of the projects in the biological hydrogen production portfolio was on biological methods to produce hydrogen from biomass resources and addressing key barriers such as low hydrogen production rates and yields as well as feedstock utilization using molecular biology and genetic engineering techniques along with improved systems engineering. Technical progress included the following:

- Successfully deleted two metabolic pathways that compete with hydrogen production, resulting in a higher specific rate of hydrogen production. (NREL)
- Doubled the volumetric productivity of in vitro enzymatic hydrogen production from starch to a peak rate of 320 mmol H_2/L/h. (Virginia Polytechnic Institute and State University)
- Identified fermentative bacterial cultures capable of producing hydrogen from major sugars in lignocellulosic biomass hydrolysate at a hydrogen yield reaching 40% of the theoretical maximum, and an exoelectrogenic bacterial culture capable of utilizing all liquid fermentation products and generating a current density up to 15 A/m^2 of anode surface area. (Ohio State University)

Solar-Thermochemical Hydrogen Production

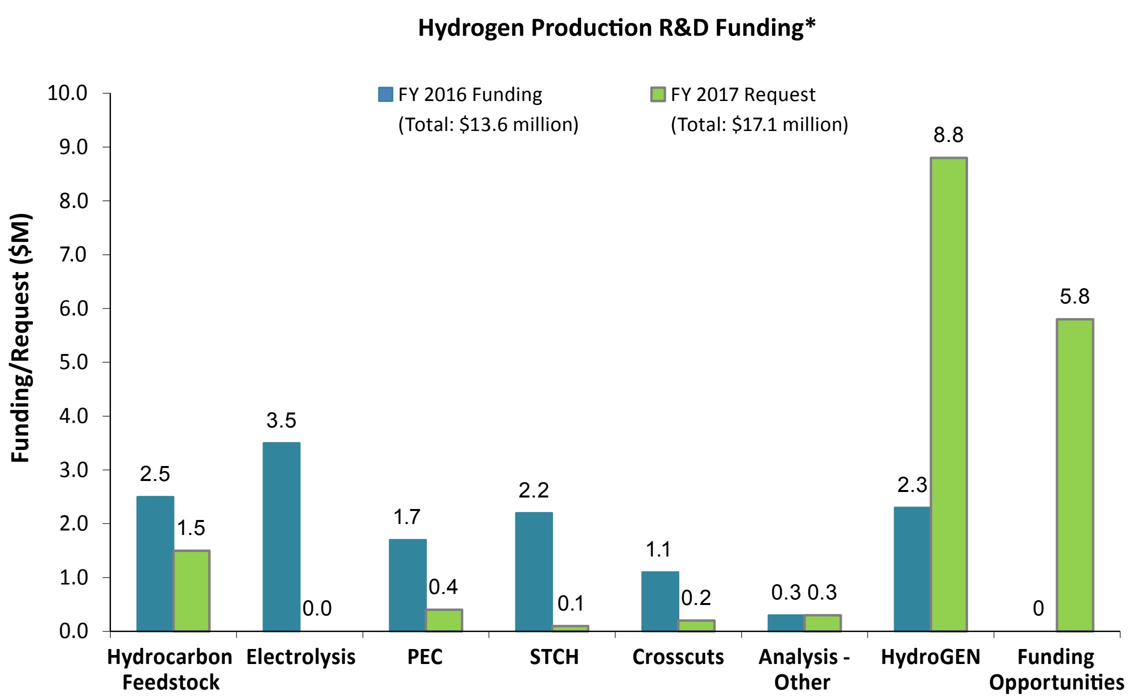
Efforts in these projects were directed toward performance characterization of water splitting by novel, non-volatile metal-oxide based reaction materials and development of new reactor concepts to optimize efficiency of the reaction cycles as well as advancing the electrolytic step of the hybrid sulfur thermochemical cycle. Technical progress included the following:

- A prototype 3 kW cascading pressure reactor/receiver was designed, and the approach to materials discovery and engineering of thermochemical properties was extended such that greater than 50 new compounds have been synthesized and characterized. (Sandia National Laboratories)
- Successful collaboration between the National Science Foundation (NSF) and DOE accelerated materials discovery and characterization with 955 binary spinal structures and 1,343 binary perovskite materials screened for solarthermal water splitting potential. Eight materials have been synthesized for experimental validation. (University of Colorado Boulder)
- Trade-off studies were completed that resulted in a baseline design that permits continuous hydrogen production at high thermal efficiency and demonstrates potential to meet DOE hydrogen cost goals. Detailed flowsheets were designed and modeled in Aspen Plus™ for both 2015 and 2020 plant design cases. (Savannah River National Laboratory)

BUDGET

The FY 2016 appropriation for the Hydrogen Production and Delivery programs was $25.4 million. Funding was distributed approximately evenly between Production and Delivery, with Production allocated $13.6 million and Delivery allocated $11.9 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 2017 is $28.1 million, with $17.1 million slated for Production projects. The estimated budget breakdown for Production funding in FY 2016 and FY 2017 is shown in Figure 2.

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 electrolysis, and direct water-splitting through PEC and STCH processes. Previous projects



Subject to appropriations, project go/no-go decisions, and competitive selections. Exact amounts will be determined based on research nd development progress in each area.

FIGURE 2. Budget breakdown for FY 2016 through FY 2017

scheduled for completion within the next two years include FY 2014 FOA projects in areas of bio-derived feedstock conversion and PEC and STCH water splitting, four joint NSF/FCTO projects in solar water splitting, and five incubator projects in topics including advanced electrolysis and reversible fuel cells. Moving forward into FY 2017, the Production and Delivery emphasis on renewable technologies is expected to ramp up with the establishment of the HydroGEN consortium, part of the DOE Energy Materials Network, to accelerate the discovery and development of innovative materials for enabling commercial-scale renewable hydrogen production through electrochemical, photoelectrochemical, and thermochemical water-splitting processes.

FY 2017 PLANS

General Hydrogen Production program plans for FY 2017 include the following:

- Initiate projects selected in the FY 2016 FOA.
- Continue to demonstrate substantial progress in the six Production projects selected in the FY 2014 FOA, the five projects selected under the 2015 Incubator FOA, and 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, the DOE Office of Science's BES program, and the DOE Advanced Research Projects Agency-Energy.
- Ramp up research efforts centered on the HydroGEN consortium on advanced water-splitting technologies, including enhancement of core capabilities in materials–device and system-level development for advancing the technology readiness level in technologies including advanced low-temperature electrolysis, advanced high-temperature electrolysis, as well as direct PEC and STCH water splitting.

Important pathway-specific milestones planned for FY 2017 in the Hydrogen Production program projects include the following:

- Demonstrate >500 h 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-bandgap, thin-film absorbers with PEC solar photocurrent densities $\geq$13 mA/cm^2 to enable >16% solar-to-hydrogen conversion efficiency.

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