II.0 Hydrogen Production Sub-Program Overview

Introduction

The Hydrogen Production activity in Fiscal Year 2009 was focused on developing hydrogen production technologies that enable the introduction and long-term viability of hydrogen as an energy carrier for portable power, stationary power and transportation applications. A variety of feedstocks and technologies are being pursued.

Four DOE offices have been engaged in research and development (R&D) relevant to hydrogen production. The Office of Energy Efficiency and Renewable Energy (EERE) is developing technologies for producing hydrogen from bio-derived renewable liquids and by electrolysis of water, as well as centralized renewable production options that include water electrolysis integrated with renewable power (e.g., wind, solar, hydroelectric, and geothermal), biomass gasification, solar-driven high-temperature thermochemical water splitting cycles, direct photoelectrochemical water splitting, and biological processes. The Office of Fossil Energy (FE) is focused on advancing the technologies needed to produce hydrogen from coal-derived synthesis gas, including co-production of hydrogen and electricity as well as carbon sequestration. The Office of Nuclear Energy (NE) is developing hydrogen production using heat from an advanced nuclear reactor through high-temperature steam electrolysis and thermochemical water splitting cycles. The Office of Science's basic research program emphasizes fundamental understanding of biological and biomimetic hydrogen production, photoelectrochemical water splitting, catalysis, and membranes for gas separation.

Goal

Research and develop low-cost, highly efficient hydrogen production technologies from diverse, domestic sources, including coal (with sequestration), nuclear and renewable sources.

Objectives

Reduce the cost of hydrogen to $2.00-$3.00/gasoline gallon equivalent (gge) dispensed at the pump. This goal applies to all production technology pathways. Technologies are being researched to achieve this goal in timeframes relative to their current states of development. The dispensed cost target of several hydrogen production pathways are summarized in the following table.

Production Pathway	Production Site	Near-Term Hydrogen Cost Target		Long-Term Hydrogen Cost Target	
		Year	$/gge	Year	$/gge
Bio-Derived Liquids	Distributed	2014	$3.80	2019	$3.00
Electrolysis	Distributed	2014	$3.70	2019	$3.00
Biomass Gasification	Central	2014	$3.30	2019	$2.10
Electrolysis	Central	2014	$4.80	2019	$3.00
Solar Thermochemical	Central	N/A	N/A	2019	$4.00

N/A - not applicable

- Since previous work demonstrated the $3.00/gge cost target could be met from distributed natural gas, DOE no longer funds R&D in this area, and industry will take the lead as the market develops.
- By 2019, verify the potential for high-temperature thermochemical cycles driven by concentrated solar energy to be competitive in the long term.
- Develop advanced renewable photoelectrochemical and biological hydrogen generation technologies. By 2020, verify the feasibility of these technologies to be competitive in the long term.
- By 2016, prove the feasibility of a near-zero emissions, high-efficiency plant that will produce both hydrogen and electricity from coal and that also reduces the cost of hydrogen from coal by 25 percent compared to current technology.

FY 2009 Accomplishments

Biomass and Bio-Derived Liquids Pathways

- United Technologies Research Center exceeded 95% conversion of cellulosic biomass (yellow poplar) with 74% hydrogen selectivity.
- Pacific Northwest National Laboratory increased hydrogen yields to >92% by optimizing catalyst formulations and reaction conditions for vapor phase reforming at low pressure.
- National Renewable Energy Laboratory (NREL) completed pilot unit parametric studies and updated their Aspen Plus gasification model. With this update, the model now predicts approximately 50% less char formation, which is closer to measured values.
- NREL demonstrated partial oxidation of a 90 wt% bio-oil/10 wt% methanol mixture in a bench-scale reactor system. Non-catalytic gas-phase oxidation of bio-oil followed by catalytic reforming of the gas/vapor intermediate resulted in 85-90% carbon-to-gas-conversion.

Electrolysis

- Giner Electrochemical Systems demonstrated 1,000-hour single cell membrane activity operating at 80°C, 300 psig, 1,500 mA/cm^2 current density, and 75% efficiency (lower heating value, LHV). The fluoride loss rate during the test was used to project a membrane lifetime of 45,000 to 55,000 hrs.
- Giner Electrochemical Systems is testing a new biphenyl sulfone membrane which costs about half that of their current membranes. Single cell tests show 75% efficiency (LHV) under nominal operating conditions (80°C, 300 psig) and long-term durability tests are planned.
- NREL researchers developed standardized, international electrolyzer testing protocols that are currently under peer review.
- NREL conducted an independent analysis of distributed and centralized hydrogen production costs. The analysis showed an estimated cost of $4.90 - $5.70/gge for distributed production and $2.70 - $3.50/gge for central production, at the plant gate.

Solar Pathways

- NREL and the University of Colorado tested a prototype aerosol reactor for thermochemical water splitting “on-sun.”
- University of Colorado decreased the water splitting temperature by 200°C by using atomic layer deposition for the CoFe ferrite on alumina.
- Technoeconomic analysis was completed on several high-temperature thermochemical cycles resulting in the down-selection of the ZnO cycle and identification of critical tasks for the remaining cycles. Resources were redirected to the critical tasks.
- Directed Technologies, Inc. completed a boundary level technoeconomic analysis for the photoelectrochemical (PEC) direct water splitting pathway. The analysis identified several pathways to meet hydrogen production cost targets using PEC. Projected hydrogen costs range from about $4 to $10/gge.
- The PEC Working Group developed standardized test protocols for PEC materials. The test protocols are currently under peer review and scheduled for January 2010 publication.
- NREL conducted a Go/No-Go decision analysis and eliminated from further study the Co-Al-Fe-O PEC material class that had initially yielded promising results in combinatorial synthesis and screening tests. Resources were redirected towards synthesis and characterization of more promising carbide and nitride materials.
- University of California, Berkeley completed the cloning of the previously identified Tla2 gene. This gene enables 15% solar to chemical energy conversion in microalgae. The high conversion brings the microalgae effort halfway to the theoretical conversion maximum of 30%.
- Directed Technologies, Inc. completed a boundary level techno-economic analysis for hydrogen production cost including four different biological processes: photolytic, photosynthetic,

fermentation, and microbial aided electrolysis. In addition, the analysis evaluated an integrated approach that combined multiple processes. The results show several pathways that can meet hydrogen production cost targets in the long term with costs ranging from about $3 to about $12/gge.

- Penn State University and NREL developed and demonstrated an integrated system that improves hydrogen molar yield via fermentation by a factor of four to eight, surpassing the DOE 2013 target. The system uses dark fermentation of lignocellulosic corn stover followed by a microbial electrolysis cell reaction.
- NREL researchers immobilized sulfur-deprived algal cells in a polymeric, biodegradable matrix and demonstrated continuous hydrogen production for a total of 300 hours under aerobic conditions with a conversion efficiency of approximately 0.7% at low light intensity. Previous aerobic production, using suspension cultures, showed no hydrogen generation.

Fossil Energy

- The Office of Fossil Energy has developed and implemented a standardized testing protocol for membrane separations.
- Eltron Research, Inc. and Southwest Research Institute® have demonstrated, in bench-scale tests, membranes that have the ability to meet nearly all of FE's 2010 hydrogen separation targets. Preliminary cost estimates of the Eltron membrane show that the technology could be competitive with conventional technology. Southwest Research Institute® has also produced self-supported Pd-Cu alloy membranes that have reduced membrane thickness from 25 microns (2007 state-of-the-art) to 5 microns.
- The National Energy Technology Laboratory Office of Research and Development (ORD) completed independent verification testing of several membranes to validate performance. ORD has also conducted studies on the impact of sulfur on palladium membranes that have shown that two degradation mechanisms typically occur and that gas species concentrations throughout the membrane can impact degradation.
- Preliminary economic analysis show membranes have the potential for lower electricity cost, higher thermal efficiency, and improved CO_2 capture compared to conventional technologies.

Nuclear Energy

- Idaho National Laboratory operated their integrated laboratory-scale high temperature electrolysis unit for 45 days achieving 5,650 liters per hour peak output at 12 kWe input.
- Savannah River National Laboratory developed new operating methods that demonstrated electrolyzer operation without limitations caused by sulfur build-up.
- A team consisting of General Atomics, Sandia National Laboratories and the Commissariat à l'Énergie Atomique of France completed the integrated laboratory-scale Sulfur-Iodine thermochemical system operation. Hydrogen was produced at rates up to 30 to 40 liters per hour.

Budget

The FY 2009 budget for hydrogen production provided $38.3M for continued hydrogen production research. FE received $25M, NE $7.5M and EERE $5.8M to continue research efforts for FY 2009.

The President's FY 2010 budget realigns the Hydrogen Program to focus on nearer-term impacts to our Nation's most pressing energy needs. As part of the realignment, no funding for EERE and NE Hydrogen Production was requested. FE's request is $16.4M.

2010 Plans

- Final reports documenting progress will be issued in FY 2010. The applied R&D programs in EERE and NE will coordinate with the Office of Science, which plans up to about $50 million of basic research related to hydrogen and fuel cell technologies. Through basic science activities, a

fundamental understanding of issues related to hydrogen production, particularly in the longer term R&D areas of high temperature thermochemical, photoelectrochemical and biological processes, can help address the challenges of hydrogen production technologies. In addition, through the deployment projects funded by the American Recovery and Reinvestment Act, lessons learned related to hydrogen production technologies will be determined.

- Continue laboratory-scale research efforts on hydrogen from coal production technologies and advance hydrogen separation membrane technologies. Conduct laboratory-scale efforts on combined water-gas shift hydrogen separation systems (i.e., process intensification).

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