# 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 stationary power (e.g., backup power and combined heat-and-power systems), transportation (e.g., specialty vehicles, cars, trucks, and buses), 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.

Three DOE offices are engaged in R&D relevant to hydrogen production, including:

- The Fuel Cell Technologies (FCT) Program, within the Office of Energy Efficiency and Renewable Energy (EERE), is developing technologies for distributed and centralized renewable production of hydrogen. Distributed production options under development include reforming of bio-derived renewable liquids and electrolysis of water. Centralized renewable production options include water electrolysis integrated with renewable power generation (e.g., wind, solar, hydroelectric, and geothermal power), biomass gasification, solar-driven high-temperature thermochemical water splitting, direct photoelectrochemical water splitting, and biological processes.
- The Office of Fossil Energy (FE) is advancing the technologies needed to produce hydrogen from coal-derived synthesis gas, including co-production of hydrogen and electricity. Separate from the Hydrogen and Fuel Cells Program, FE is also developing technologies for carbon capture and sequestration, which will ultimately enable hydrogen production from coal to be a near-zero-emissions pathway.
- The Office of Science's Basic Energy Sciences (BES) program conducts research to expand the fundamental understanding of biological and biomimetic hydrogen production, photoelectrochemical water splitting, catalysis, and membranes for gas separation.
- The Office of Nuclear Energy (NE) has been conducting efforts in development of high-temperature electrolysis, under the Next Generation Nuclear Plant (NGNP) project, which also includes evaluations of other end-user applications and energy transport systems. The Nuclear Hydrogen Initiative was discontinued as a separate program in Fiscal Year (FY) 2009 after the selection of steam electrolysis as the hydrogen production pathway most compatible with the NGNP.

## GOAL

The goal of the Hydrogen Production sub-program's portfolio 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[1] of the EERE hydrogen production portfolio is to reduce the cost of 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 threshold cost of \$2–4 per gallon gasoline equivalent [gge] by

[1] Note: Targets and milestones were recently revised; therefore, individual project progress reports may reference prior targets. Some targets are still currently under revision, with updates to be published in FY 2013.

2020[2]). Technologies are being researched 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 percent compared with current technology, by 2016. The objectives of NE's efforts in hydrogen production are documented in the *Technology Roadmap for Generation IV Nuclear Energy Systems* (December 2002).[4] They include the development of high-temperature thermochemical process for hydrogen production compatible with NGNP.

## FY 2012 TECHNOLOGY STATUS AND PROGRESS

In FY 2012, significant progress was made by the EERE Hydrogen Production sub-program on several important fronts. For example:

- A Hydrogen Production Expert Panel workshop was held to assess technology status of production technologies and formulate recommendations for enabling pathways forward for the widespread production of affordable low-carbon hydrogen.
- A new version of the Hydrogen Analysis (H2A v3) Model was published with updated economic data and assumptions, and with all costs converted to 2007 dollars to be consistent with the cost basis for the DOE FCT Program's cost threshold for hydrogen production and delivery.
- Updated economic and cost-sensitivity analyses using H2A v3 were performed incorporating the most up-to-date information on pathway technologies and technology-readiness projections; the resulting case studies were used to revise the pathway-dependent cost status and targets for the Hydrogen Production sub-program's chapter of the *Multi-Year Research, Development and Demonstration Plan (MYRD&D Plan),* currently in final review.
- Important technical advances were made by the principle investigators in all the hydrogen production projects in the sub-program portfolio.

More details of the technology status and progress are provided in following sections.

### Hydrogen Production Expert Panel

A Hydrogen Production Expert Panel—composed of world leaders in hydrogen production technologies from industry, academia and the national laboratories—was established as a subcommittee of the Hydrogen & Fuel Cell Technical Advisory Committee (HTAC). In May 2012, Secretary of Energy Steven Chu kicked off a workshop held by the panel to formulate recommendations to HTAC on enabling pathways for the widespread production of affordable low-carbon hydrogen, both for near- and long-term markets. The objectives of the workshop were to: (1) evaluate current status of hydrogen production technologies; (2) identify remaining technological and economic challenges; (3) prioritize R&D needs; and (4) strategize how to best leverage R&D among U.S. Department of Energy Offices and with other agencies. A summary report resulting from the workshop is under final review by the Hydrogen Production Expert Panel for submission to HTAC.

[2] Hydrogen Threshold Cost Calculation, Hydrogen and Fuel Cells Program Record #11007, U.S. Department of Energy, 2012, http://www.hydrogen.energy.gov/pdfs/11007_h2_threshold_costs.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] *A Technology Roadmap for Generation IV Nuclear Energy Systems*, Office of Nuclear Energy, U.S. Department of Energy, December 2002, http://www.ne.doe.gov/genIV/documents/gen_iv_roadmap.pdf.

## Production Cost Status and Targets

The status and targets for the projected cost of hydrogen production based on the pathway-specific H2A v3 case studies completed in FY 2012 are shown in Table 1. The technoeconomic assumptions used in these case studies can be found online for each pathway at http://www.hydrogen.energy.gov/h2a_production; and these cases are also fully documented in the FCT Program's new *MYRD&D Plan* (currently in final review). As a note, the 2006 report *Distributed Hydrogen Production from Natural Gas*[5] provided the basis for DOE to discontinue R&D of steam methane reforming for hydrogen production—verifying that the use of existing steam methane reforming technologies in distributed hydrogen production could already meet the cost target at high-volume production; targets for this pathway are not included in Table 1. Also, targets for hydrogen production efforts in FE and NE (also not included in Table 1), along with information on the status of the technologies, are described separately in the previously cited RD&D and roadmap documents for these programs.

**TABLE 1.** Cost Status and Targets for Hydrogen Production*

| | $/gge (production costs only) | 2011 Status | 2015 Target | 2020 Target | Ultimate Production Target |
|---|---|---|---|---|---|
| Distributed | Electrolysis from grid electricity | $4.20 | $3.90 | $2.30 | $1-$2 |
| | Bio-derived Liquids (based on ethanol reforming case) | $6.60 | $5.90 | $2.30 | |
| Central | Electrolysis From renewable electricity | $4.10 | $3.00 | $2.00 | |
| | Biomass Gasification | $2.20 | $2.10 | $2.00 | |
| | Solar Thermochemical | NA | $14.80 | $3.70 | |
| | Photoelectrochemical | NA | $17.30 | $5.70 | |
| | Biological | NA | NA | $9.20 | |

*H2A v3 technoeconomic assumptions used in the projected cost status and targets for hydrogen production are consistent with the FCT Program's new MYRD&D Plan – currently in final review; apportionment of threshold cost: $1-2/gge for production, $1-2/gge for delivery is consistent with a Hydrogen and Fuel Cells Program record currently in final review; new H2A v3 case studies are published at http://www.hydrogen.energy.gov/h2a_production.

Reductions in the projection costs for hydrogen production in several of the nearer term pathways have been realized through continued technical progress in these technologies, as illustrated in Figure 1. Specific technical progress achieved in FY 2012 in both the nearer and longer term hydrogen production pathways is addressed in the following sections.

## Separation Processes and Biomass Gasification

Projects in the separations area focused on the development of hydrogen separation membranes for use in a water-gas shift membrane reactor, and on the development and demonstration of a biogas cleanup system. Biomass gasification efforts focused on the development of a one-step biomass gas reforming-shift separation membrane reactor. Technical progress included:

- Demonstrated palladium-copper alloy thin film (~5 µm) membranes with a hydrogen ($H_2$) permeance of 10-15 $m^3/m^2$/hr/bar at 350°C (i.e., 50-75 scfh, at 20 psig) and a selectivity of $H_2/N_2$ of 200 to >1,000, meeting the DOE 2015 cost vs. performance target of 0.6 scfh, at 20 psi per unit dollar cost. (Media & Process Technology, Inc.)

[5] *Distributed Hydrogen Production from Natural Gas*, National Renewable Energy Laboratory, October 2006, http://www.hydrogen.energy.gov/pdfs/40382.pdf

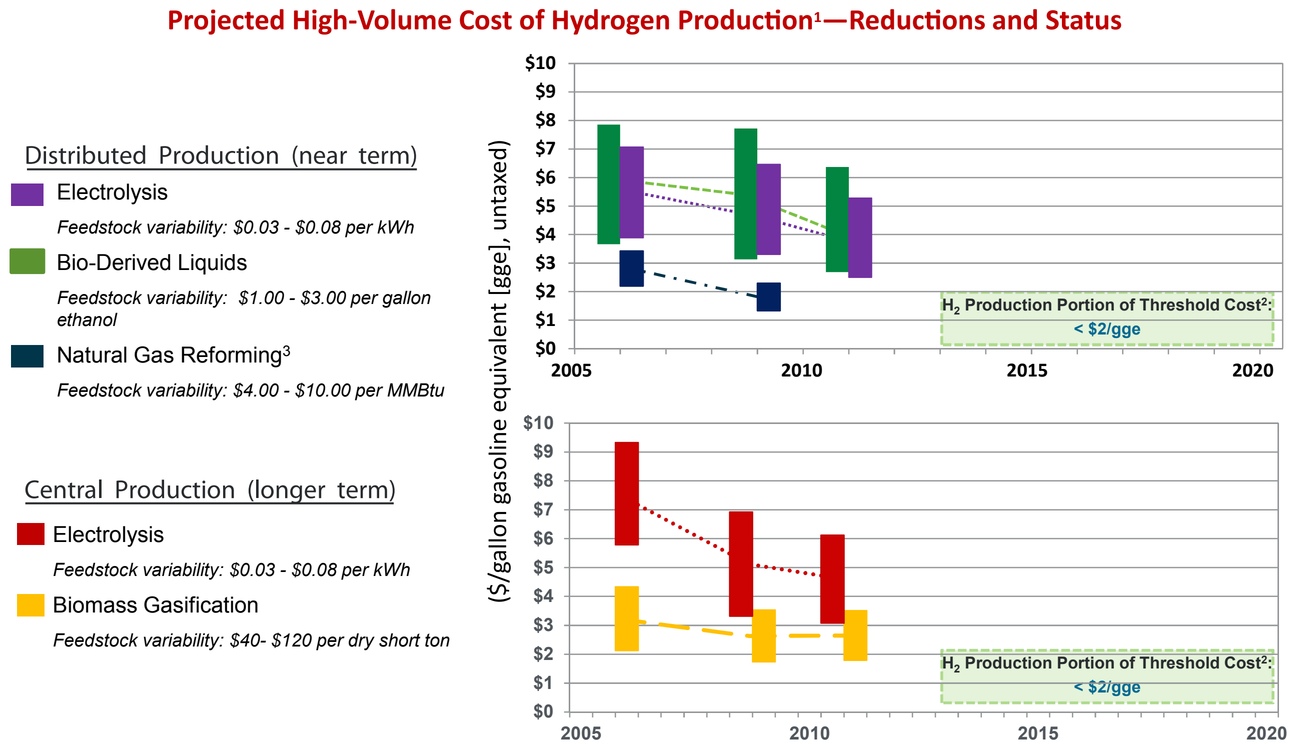



**FIGURE 1.** Hydrogen Production Cost Status. Significant progress has already been made in several hydrogen production pathways. The Hydrogen Threshold Cost represents the cost at which hydrogen fuel cell electric vehicles are projected to become competitive on a cost-per-mile basis with competing vehicles (gasoline hybrid-electric vehicles) in 2020. Notes: (i) Costs shown do not include taxes. Costs of forecourt compression, storage, and dispensing are not included for distributed technologies, and plant-gate production costs (not including transportation, compression, storage, and dispensing) are shown for centralized technologies. Projections of distributed costs assume station capacities of 1,500 kg/ day. Projections of centralized production costs assume capacities of ≥50,000 kg/day. Cost ranges for each pathway are shown in 2007 dollars, based on high-volume projections from H2A analyses, reflecting variability in major feedstock pricing and a bounded range for capital cost estimates. (ii) DOE funding of natural gas reforming projects was completed in 2009 due to achievement of the threshold cost. Incremental improvements will continue to be made by industry.

- Fabricated a 12 cubic foot/minute, skid-mounted, field-deployable prototype biogas clean-up system for removal of $H_2S$ and siloxane contaminants to less than ppmv levels using an optimized sorbent formulation. (TDA Research Inc.)
- Demonstrated through H2A modeling the potential for an up to 35% increase in $H_2$ recovery (compared to conventional pressure swing adsorption separation technology) in a one-step membrane reactor for biomass gas reforming, with a projected high volume cost of $1.82/kg $H_2$ compared to $2.00/kg $H_2$ with a pressure swing adsorption unit. (Gas Technology Institute)

### Bio-Derived Liquid Pathways

Projects in this area addressed hydrogen production through catalytic steam reforming of pyrolysis oil, and aqueous phase reforming of pyrolysis oil at moderate temperatures. Technical progress included:

- Constructed an integrated bench-scale system for the production of 100 L/h hydrogen from pyrolysis bio-oil, including all the basic unit operations as the design for a 1,500 kg/day hydrogen plant, and on-going demonstration of 100 hours of commercial catalyst performance for catalytic autothermal reforming. (National Renewable Energy Laboratory, NREL)
- Identified Pt-Co/$ZrO_2$ catalysts having potential to improve $H_2$ yields from water soluble components of bio-oil up to 2-3x the yields with other Pt-based catalysts for aqueous phase reforming. (Pacific Northwest National Laboratory)

### Electrolysis Hydrogen Production

The major emphases of the electrolysis projects were on cost reduction and efficiency improvement through cell and stack optimization, higher-pressure operations, and validation of integration with renewable resources. Technical progress included:

- Completed 5,000-hour life-test with dimensionally stable membranes (DSM™) operating at 80°C and 300 psid, for use in advanced electrolyzer stacks with an order of magnitude cost reduction in membrane supports, compared with legacy designs without DSM™. (Giner Inc.)
- Manufactured an electrolyzer system incorporating low-cost stack components into a high-efficiency hydrogen production system, and completed >100 hours of field testing at the NREL test facility for renewable integration, verifying improvements brought about through sub-program investments. (Giner Inc. and NREL)
- Fabricated over 3,000 cells utilizing new flow field design resulting in >20% part cost savings (corresponding to a 12% stack cost reduction over a three year period), and assembled these improved cells into production stacks. (Proton Onsite)

### Photoelectrochemical (PEC) Hydrogen Production

The broad focus of projects in this area was on developing viable PEC material systems and prototypes with improved efficiency and durability. Technical progress included:

- Demonstrated extended durability in high-efficiency III-V crystalline systems for PEC hydrogen production from a baseline of ~20 hours up to >100 hours, achieved through innovative theory-inspired surface ion nitride treatments of the crystalline surfaces for passivation against corrosion; the enhanced stability was demonstrated under operating conditions consistent with solar-to-hydrogen (STH) conversion efficiencies exceeding 10%. (NREL)
- Verified 420 hours durability in low cost thin-film copper-gallium-diselenide PEC photoelectrodes under simulated sunlight, operating at a current density equivalent to 5% STH conversion, exceeding the 300 hours target for 2012, and up from the baseline of 200 hours in 2011. This result indicates the viability of lower-cost thin-film material systems for efficient PEC water splitting. (MVSystems/University of Hawaii)
- Demonstrated highly stable $H_2$ evolution by core-shell $MoO_3$-$MoS_2$ nanowires, with no degradation observed in acidic electrolyte through 10,000 cycles of testing at 10 $mA/cm^2$ (i.e., conditions consistent with STH conversion efficiencies >12%). This result indicates the long-term viability of theory-inspired nano-structured devices for PEC water spitting. (Stanford U.)

### Biological Hydrogen Production

Projects in this area encompassed a portfolio of photobiological and fermentative production methods that use various algal, cyanobacterial, and bacterial microorganisms that produce hydrogen through splitting water or using biomass resources. Technical progress included:

- Achieved improved hydrogen fermentation rates through optimizing reactor design and operating conditions, resulting in a 2-fold increase in hydrogen production through higher cellulose feedstock loading. This will serve as the foundation for future efforts to scale up hydrogen fermentation systems. (NREL)
- Identified and characterized the gene mutation that enabled light utilization efficiency of 25% in the *tla3* mutant strain of algae. These findings will be applied to reducing chlorophyll antenna size to increase the utilization efficiency of incident solar light energy. (UC Berkeley)
- Increased hydrogen evolution activity from ~50 nmol $H_2$/mg lysate/hour to ~200 nmol $H_2$/mg lysate/hour thorough the genetic modification of an environmentally-isolated hydrogenase enzyme. This is

a significant step in improving the mechanisms of hydrogen production in microbes. (J. Craig Venter Institute, in collaboration with NREL)

- Demonstrated light-induced hydrogen production by a cyanobacterial hydrogenase expressed in algae. This is a critical step in engineering algae to produce high levels of hydrogen using the more oxygen-tolerant hydrogenases of other species. (NREL)

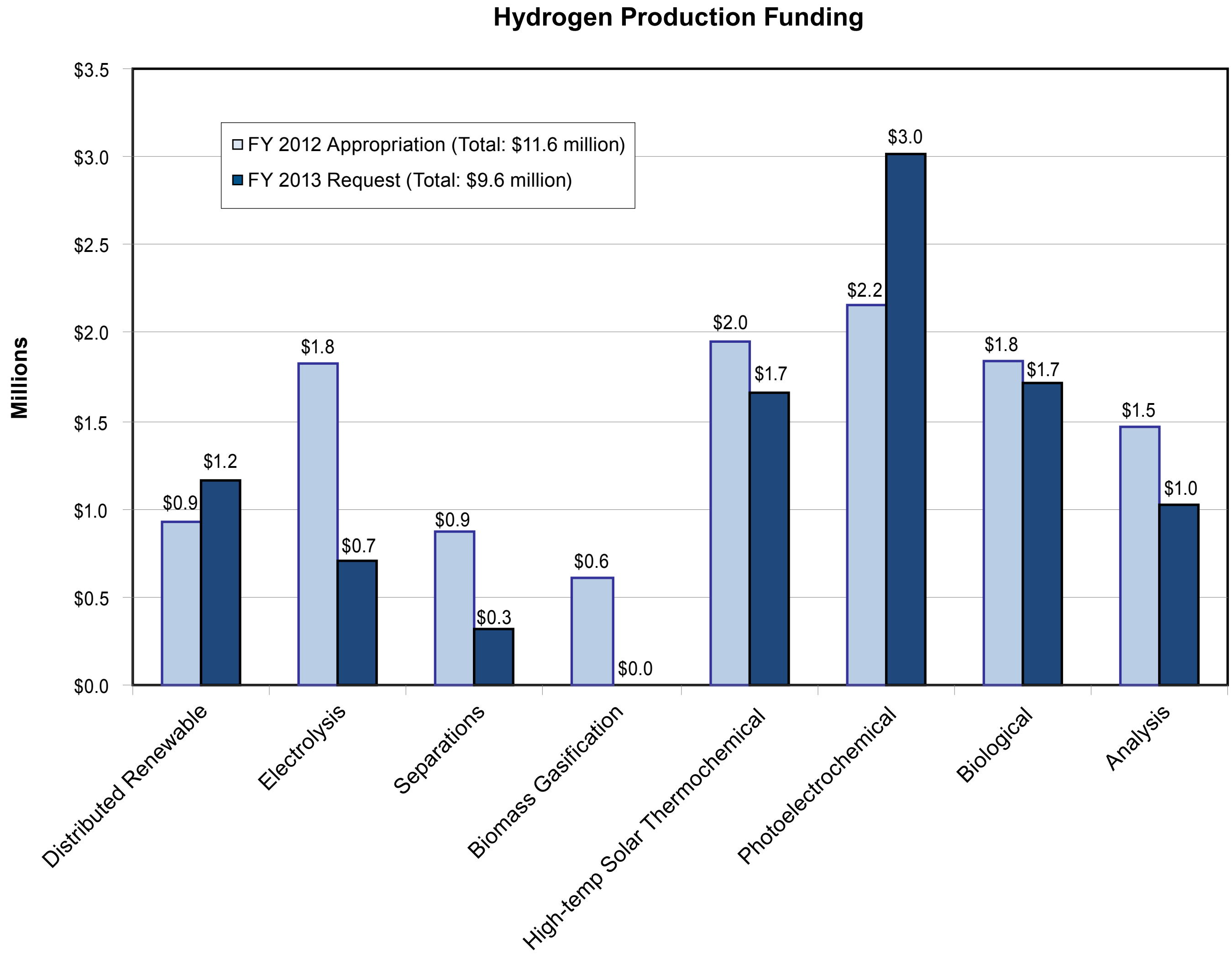
### Solar-Thermochemical Hydrogen Production

Efforts in these projects were directed toward improving reactor designs, improving voltage and overall efficiency, and addressing membrane crossover issues. Technical progress included:

- Experimentally verified by Raman spectroscopy that hercynite reaction materials follow a redox mechanism through stable aluminates; and demonstrated hydrogen production at reduced temperatures as low as 1,360°C for up to 23 thermal reduction cycles using this novel material. (U. of Colorado, Boulder)
- Developed a phase-change thermal energy storage approach using NaCl for the sulfur-ammonia thermochemical hydrogen production reaction cycle to allow 24/7 operation of the cycle. The molten NaCl approach will provide a large amount of thermal capacity (481 kJ/kg) at temperatures up to 800°C. (SAIC)
- Designed a particle bed reactor featuring particle cycling, high solar utilization, and theoretical solar efficiency >30% over a broad range of direct normal insolation levels from 1,000 $W/m^2$ (corresponding to full midday sun) down to 400 $W/m^2$. (Sandia National Laboratories)
- Demonstrated of a Faradaic efficiency >95% in the electrolysis step for the CuCl reaction cycle, with a stable cell potential at 0.7 V and the current density of 0.5 $A/cm^2$ using a Nafion®-based membrane. No copper deposits on any of the cell components were observed after a 36 hour test, indicating a significant mitigation of copper-crossover as a primary technological barrier. (Argonne National Laboratory)

## BUDGET

The FY 2012 appropriation for the Hydrogen Production and Delivery sub-program of the FCT Program was $17.4 million. Funding was distributed approximately 67% to 33% between Production and Delivery, respectively (the same distribution used in FY 2011). Production funding has increasingly focused on early development, long-term, renewable pathways such as photoelectrochemical, biological, and solar-thermochemical hydrogen production. This trend, as shown in the budget breakdown chart in Figure 2, is expected to continue in FY 2013 as projects focused on separations, biomass gasification, and electrolysis transition from the R&D portfolio to Small Business Innovation Research and Technology Validation funding venues. $9.6 million in funding is planned for Hydrogen Production from the FY 2013 request.




## FY 2013 PLANS

General Hydrogen Production sub-program plans for FY 2013 include:

- Continue the emphasis on addressing major challenges in hydrogen production. Performance and durability enhancements in materials and systems will remain a priority, and cost reductions will be achieved through process optimization for all production pathways and technologies. Additional efforts will also address reducing the cost of materials and capital equipment.
- Continue to develop and update case studies for hydrogen production pathways using H2A v3 to identify and address cost barriers and technical challenges.
- Continue to develop and refine materials characterization protocols and performance metrics for early development technologies.
- Use recommendations from the HTAC Hydrogen Production Expert Panel to inform portfolio planning (including coordination with other agencies and DOE Offices to leverage R&D investments in hydrogen production technologies).
- Continue EERE coordination with the Office of Science, which plans approximately $50 million in 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 photoelectrochemical and biological processes) can help address the challenges of hydrogen production. Coordination of the solar-hydrogen-related fundamental research activities in the Office of Science's Solar Fuels Innovation Hub with the hydrogen production systems-oriented R&D in EERE will be a high priority.
- Initiate new starts in Production Analysis and R&D through competitive funding opportunity announcements.

Some important pathway-specific milestones planned for FY 2012 in the Hydrogen Production sub-program projects include:

- Extend lifetime measurements of $GaInP_2$/GaAs devices for photoelectrochemical production of hydrogen and determine the durability benchmarked against the target of a 500-hour operational lifetime under conditions equivalent to 10% STH efficiency.
- Verify bipolar plate designs for electrolyzer stacks with sufficient performance and durability to enables cost projections based on early prototypes meeting production target of $3.70/kg.
- Advance the studies of integrated systems for biological hydrogen production, first improving hydrogen production by fermentation of biomass-based substrates by at least 20%, then demonstrating that a prototype microbial reverse-electrodialysis electrolysis cell reactor can produce hydrogen using the fermentation effluent without grid electricity inputs.

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