Hydrogen Fuel R&D Subprogram Overview

INTRODUCTION

The Hydrogen Fuel Research and Development (R&D) subprogram focuses on R&D to reduce the cost and improve the reliability of technologies used to produce and store hydrogen from diverse domestic energy resources. In support of R&D needs identified through the U.S. Department of Energy's (DOE's) H2@Scale efforts, the Hydrogen Fuel R&D subprogram is developing a set of hydrogen production and storage technology pathways. The subprogram addresses technical challenges through a portfolio of projects in two R&D areas:

- **Hydrogen production** addresses low-cost, highly efficient hydrogen production technologies that utilize diverse domestic sources of energy. R&D activities include advanced water splitting and innovative concepts such as biological hydrogen production. The former is predominantly coordinated through the HydroGEN Advanced Water Splitting Materials consortium (HydroGEN) to accelerate research, development, and deployment of advanced water splitting technologies for clean, sustainable hydrogen production.
- **Hydrogen storage** addresses cost-effective onboard and offboard hydrogen storage technologies with improved energy density and lower costs. R&D activities include high-pressure compressed storage, materials-based storage, and hydrogen carriers. The latter two are coordinated through the Hydrogen Materials—Advanced Research Consortium (HyMARC) to accelerate the discovery of breakthrough hydrogen storage materials.

In Fiscal Year (FY) 2019, hydrogen production projects focused primarily on R&D for advanced water splitting materials and systems through HydroGEN, which is part of the DOE Energy Materials Network. Production pathways under investigation include four advanced water splitting (AWS) technologies: high- and low-temperature electrolysis (HTE, LTE), direct solar thermochemical hydrogen production (STCH), and photoelectrochemical (PEC) water splitting. Additional work outside of HydroGEN included R&D on microbial-based processes utilizing biomass and waste-stream feedstocks and efforts leveraging electrolysis technology for carbon dioxide (CO_2) reduction to useful chemicals and fuels. Hydrogen storage projects in FY 2019 focused on materials-based hydrogen storage R&D through HyMARC and on advanced tanks through innovative approaches to develop low-cost carbon fiber precursors. Large-scale hydrogen storage through newly initiated hydrogen carriers projects and storage technologies for medium- and heavy-duty transportation were additional focus areas in FY 2019.

GOALS

The Hydrogen Fuel R&D subprogram goals are to develop:

- Low-cost, highly efficient technologies for hydrogen production from diverse domestic resources for both centralized and distributed production applications
- Innovative, low-cost, and energy-dense hydrogen storage technologies for transportation and stationary applications, including bulk hydrogen storage and advanced hydrogen storage materials for medium and heavy-duty transportation and energy transport.

OBJECTIVES

The Hydrogen Fuel R&D subprogram evaluates its project portfolio with respect to its potential to meet DOE's ultimate cost targets of <$2 per kilogram of hydrogen (or gasoline gallon equivalent, gge) for hydrogen production and $8/kWh for onboard hydrogen storage systems while achieving 2.2 kWh/kg and 1.7 kWh/L for hydrogen storage system gravimetric and volumetric energy densities, respectively. Interim objectives, consistent with DOE's H2@Scale vision, include:

- Reduce the cost of hydrogen production from diverse domestic resources to <$2/kg (with a near-term target of <$7/kg and an ultimate target of <$4/kg for delivered and dispensed hydrogen). This cost is independent of the technology pathway and takes into consideration a range of assumptions for fuel cell electric vehicles to be competitive.

- Develop onboard hydrogen storage systems achieving 1.8 kWh/kg and 1.3 kWh/L for gravimetric and volumetric densities, respectively, at a cost of $9/kWh by 2025.

FY 2019 TECHNOLOGY STATUS AND ACCOMPLISHMENTS

The Hydrogen Fuel R&D subprogram actively monitors technical progress achieved through the hydrogen production and storage R&D project portfolios and incorporates that progress into the status of the technology with respect to performance metrics such as cost, efficiency, and energy density. In FY 2019, several analyses were conducted to assess technology status and progress, as described below.

The global hydrogen market is, at present, largely supplied from natural-gas-derived hydrogen. However, electrolysis shows promise as an economical option for large-scale hydrogen production, using only water and electricity as inputs. In FY 2019, Strategic Analysis, Inc. and the National Renewable Energy Laboratory (NREL) prepared case studies of the projected current (2019) and future (2035) high-volume cost of polymer electrolyte membrane (PEM) hydrogen production using the recently revised Hydrogen Production Analysis Model (H2A) Version 3.2018.[1] Figure 1 shows the results of this analysis for several near- and mid-term PEM electrolysis production pathways. Four case studies were conducted: two distributed production (1,500 kg H_2/day) and two central production (50,000 kg H_2/day) cases for both projected current (2019) and projected future (2035) technology years. All cases assume a high-volume manufacturing rate of 700 MW/year. Hydrogen production costs for two solid oxide electrolysis (SOE) baseline cases were also modeled using H2A Version3.2018 and are shown in Figure 2.

As can be seen in Figure 1 and Figure 2, electricity is the largest cost contributor for hydrogen produced via electrolysis, which indicates the importance of increasing electrical efficiency and taking advantage of low-cost electricity when available. To further demonstrate the effect of electricity price on hydrogen cost, each case was run in H2A with a set price of $0.03/kWh of electricity. Continued early-stage R&D is needed to enable the innovations essential for reducing cost in other large-scale hydrogen production technology pathways utilizing diverse and sustainable domestic resources.

Figure 3 shows the results of an FY 2019 analysis that modeled the cost of onboard high-pressure compressed hydrogen storage systems at annual manufacturing volumes of 100,000 and 500,000 from 2013 to 2019. This comparison highlights a steady decrease in the cost of hydrogen storage systems, including more than a 20% reduction since 2013. Cost savings are primarily due to the development of lower-cost carbon fiber and resin, improved carbon fiber usage, and integrated balance of plant components.[2] This cost analysis also included an update on the basis year from 2007 U.S. dollars to 2016 U.S. dollars to provide a consistent basis for comparison with other program offices. While R&D has enabled a 20% cost reduction in these systems, cost and energy density are still the two main challenges for compressed hydrogen storage systems. Low-cost carbon fiber precursor R&D is one approach to achieve additional cost savings in this area. However, because hydrogen gas has a theoretical limit on energy density, addressing this challenge requires approaches beyond compressed hydrogen storage. The Program's R&D portfolio in materials-based storage, through HyMARC, is enabling advances in the hydrogen storage field with the potential to simultaneously satisfy the Program's targets for cost and energy density.

[1] H2A Production models and case studies: https://www.nrel.gov/hydrogen/h2a-production-models.html
[2] DOE Hydrogen and Fuel Cells Program Record 19008 (2019), https://www.hydrogen.energy.gov/pdfs/19008_onboard_storage_cost_performance_status.pdf

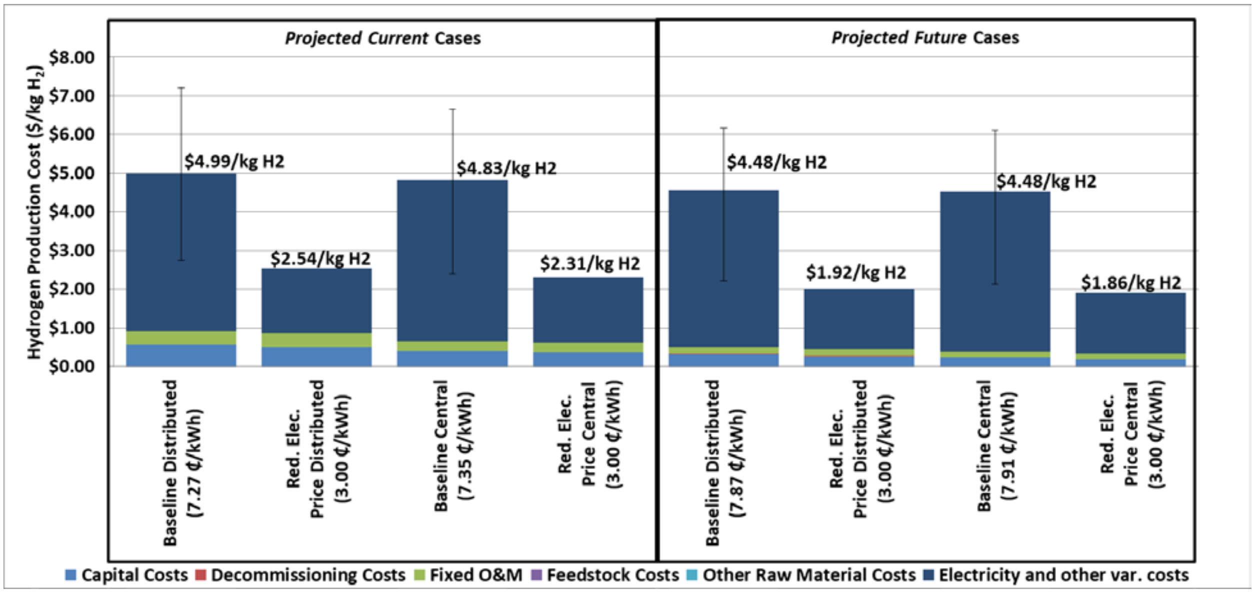

Figure 1. Status for the high-volume projected costs of PEM hydrogen production

Range of hydrogen production costs, untaxed, for near- to mid-term distributed and centralized pathways. Hydrogen production cost for PEM electrolysis (2016 U.S. dollars/kg) case studies with effective electricity prices listed for each case. Further, a cost breakdown is shown for each case at a reduced electricity price of $0.03/kWh. Error bars were determined by Monte Carlo analysis (baseline cases only).

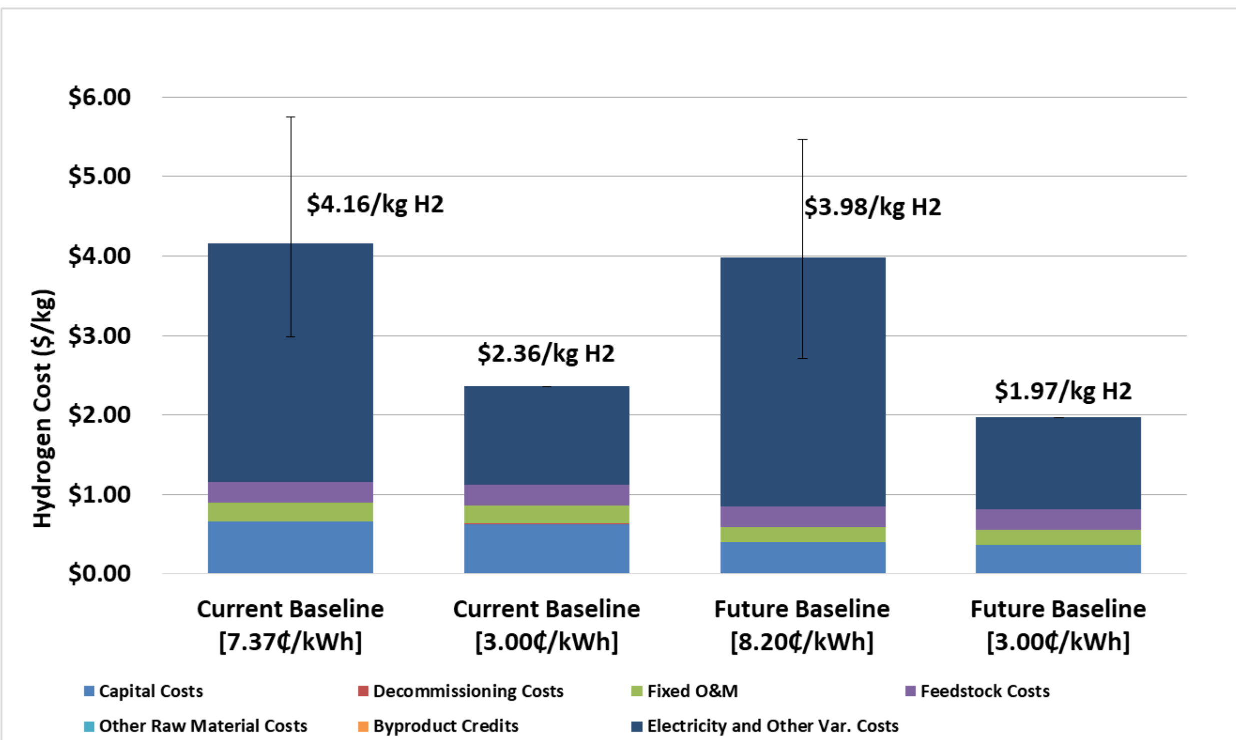

Figure 2. Status for the high-volume projected costs of SOE hydrogen production

Range of hydrogen production costs, untaxed, for near- to mid-term centralized pathways. Hydrogen production cost for SOE (2016 U.S. dollars/kg) case studies with effective electricity prices listed for each case. Further, a cost breakdown is shown for each case at a reduced electricity price of $0.03/kWh. Error bars were determined by Monte Carlo analysis (baseline cases only).

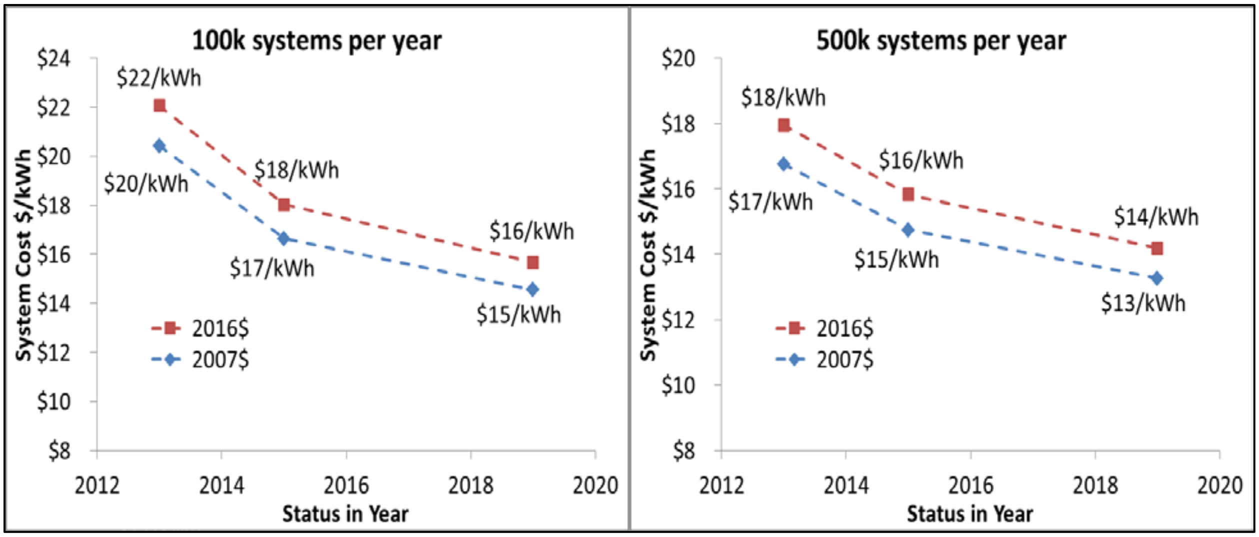

Figure 3. Comparison of storage system cost status in 2007 U.S. dollars (2007$) and 2016 U.S. dollars (2016$) as reported in 2013,[3] 2015,[4] and 2019. Costs are for annual productions of 100,000 units (left) and 500,000 units (right).

Subprogram-Level Accomplishments

The Hydrogen Fuel R&D subprogram made significant progress on several fronts during FY 2019. Specific examples include the following.

Hydrogen Production

- The HydroGEN consortium incorporated 11 new funding opportunity announcement (FOA)-awarded projects working across the four AWS technologies bringing the total to 31 active projects. The portfolio comprises seven companies and 30 universities currently leveraging the capabilities and expertise of six core national laboratories aiming to accelerate materials research in order to advance the development of water splitting technologies.
- The subprogram expanded the production portfolio to include three additional projects awarded through a competitive FOA: one under the Affordable Biological Hydrogen Production from Biomass Resources FOA topic (awarded to Oregon State University) and two under the Co-production of Hydrogen and Value-add Byproducts FOA topic (awarded to C-Zero, LLC, and University of Colorado Boulder).
- R&D projects in the current hydrogen production portfolio made significant progress, including advances in early-stage materials research for advanced LTE and HTE (including catalyst and membrane innovations); advances in materials research foundational to the PEC and STCH pathways (including novel energy-conversion materials and catalysts); and progress in cutting-edge metabolic engineering for enabling early-stage biological approaches for converting biomass and waste streams. The progress is described in further detail in the project-level accomplishments section below.
- The Benchmarking Team (FOA-awarded project) successfully held the first AWS Benchmarking Workshop. The workshop brought together more than 80 water splitting experts across 40 institutions to identify the critical parameters needed to define performance and stability as well as develop operational protocols.
- The subprogram established five Supernodes through the HydroGEN consortium, with at least one Supernode aligned to each AWS technology pathway. Within the Supernodes, the core labs work

[3] DOE Hydrogen and Fuel Cells Program Record 13013 (2013), https://hydrogen.energy.gov/pdfs/13010_onboard_storage_performance_cost.pdf
[4] DOE Hydrogen and Fuel Cells Program Record 15013 (2015), https://www.hydrogen.energy.gov/pdfs/15013_onboard_storage_performance_cost.pdf

collaboratively to demonstrate the power of integrating and utilizing HydroGEN capabilities to address a specific research gap. The five Supernodes began Phase 1 research in FY 2019 and relevant and impactful accomplishments have already been made.

- HydroGEN further expanded the Data Hub's repository with more than 210 users, approximately 30,000 data files, and eight public datasets. The team updated the open source codebase for the Data Hub to the latest CKAN version (2.8), providing improved functionality as well as the ability to share the Data Hub instance with other developers—enabling cross-lab and cross-Energy Materials Network development of new Data Hub capabilities.

Hydrogen Storage

- In FY 2019, the subprogram selected 11 new projects to support the advanced materials storage portfolio, H2@Scale efforts, and new priorities on medium- and heavy-duty transportation technologies. Four projects will focus on hydrogen carrier development addressing large-scale hydrogen transport and bulk storage challenges. Seven projects will focus on advanced materials for storing gaseous fuels including hydrogen and natural gas. Projects addressing natural gas storage challenges will be coordinated with the Office of Energy Efficiency and Renewable Energy's Vehicle Technologies Office. All of the 11 advanced materials projects selected in FY 2019 will work closely with HyMARC to avoid duplication of efforts and utilize the consortium's extensive theoretical, experimental, and characterization resources.
- The subprogram completed go/no-go decisions on four seedling projects selected through FOAs in FY 2016 and 2017. Two projects met their go criteria and were advanced from Phase 2 to 3; one met its go criteria to advance from Phase 1 to 2; and one did not not meet its go criteria and has been discontinued. All the seedling projects from FY 2016 and 2017 have now completed their Phase 1 efforts, with four moving on to Phase 2. Two of those projects have advanced to Phase 3. The two remaining seedling projects in Phase 2 are scheduled to complete their Phase 2 efforts in early FY 2020.

New Project Selections

In FY 2019, the Hydrogen Fuel R&D subprogram added 25 projects to the portfolio. Eleven projects will address hydrogen storage R&D in hydrogen carriers and advanced materials for gaseous fuel storage. Fourteen will address hydrogen production R&D in advanced water splitting, microbial processes, and the co-production of hydrogen and value-added byproducts for lower cost hydrogen. The projects are listed below.

Hydrogen Carriers

- Colorado School of Mines—High Capacity Step-Shaped Hydrogen Adsorption in Robust, Pore-Gating Zeolitic Imidazolate Frameworks
- University of Hawaii—Development of Magnesium Borane Containing Solutions of Furans and Pyroles as Reversible Liquid Hydrogen Carriers
- University of Southern California—Hydrogen Release from Concentrated Media with Reusable Catalysts
- Washington State University—A Reversible Liquid Hydrogen Carrier System Based on Ammonium Formate and Captured CO_2

Advanced Storage for Gaseous Fuels

- University of Michigan—Optimal Adsorbents for Low-Cost Storage of Natural Gas: Computational Identification, Experimental Demonstration, and System-Level Projection
- Northwestern University—Theory-Guided Design and Discovery of Materials for Reversible Methane and Hydrogen Storage
- University of Delaware—Methane Storage with Porous Cage-Based Composite Materials

- Montana State University—Heteroatom-Modified and Compacted Zeolite-Templated Carbons for Gas Storage
- University of South Florida—Metal-Organic Frameworks Containing Frustrated Lewis Pairs for Hydrogen Storage at Ambient Temperature
- Pennsylvania State University—Developing New NG Super-Absorbent Polymer (NG-SAP) for a Practical NG Storage System with Low Pressure, Ambient Temperature, and High Energy Density
- University of South Florida—Uniting Theory and Experiment to Deliver Flexible MOFs for Superior Methane (NG) Storage

Advanced Water Splitting

- Georgia Institute of Technology—Interface and Electrode Engineering for Durable, Low Cost Alkaline Anion Exchange Membrane Electrolyzers
- Nexceris, LLC—Advanced Coatings to Enhance the Durability of SOEC Stacks
- Redox Power Systems, LLC—Scalable High-Hydrogen Flux, Robust Thin Film Solid Oxide Electrolyzer
- The Chemours Company FC, LLC—Performance and Durability Investigation of Thin, Low Crossover Proton Exchange Membranes for Water Electrolyzers
- The University of Toledo—Perovskite/Perovskite Tandem Photoelectrodes for Low-Cost Unassisted Photoelectrochemical Water Splitting
- University of California: Irvine—Development of Composite Photocatalyst Materials that are Highly Selective for Solar Hydrogen Production and their Evaluation in Z-Scheme Reactor Designs
- University of California: San Diego—New High-Entropy Perovskite Oxides with Increased Reducibility and Stability for Thermochemical Hydrogen Generation
- University of Florida—A New Paradigm for Materials Discovery and Development for Lower Temperature and Isothermal Thermochemical Hydrogen Production
- University of Oregon—Pure Hydrogen Production through Precious-Metal Free Membrane Electrolysis of Dirty Water
- University of South Carolina—A Multifunctional Isostructural Bilayer Oxygen Evolution Electrode for Durable Intermediate Temperature Electrochemical Water Splitting
- William Marsh Rice University—Highly Efficient Solar Water Splitting Using 3D/2D Hydrophobic Perovskites with Corrosion Resistant Barriers

Biological Production

- Oregon State University—Scalable and Highly Efficient Microbial Electrochemical Reactor for Hydrogen Generation from Lignocellulosic Biomass and Waste

Added Value Co-Production

- C-Zero, LLC—Binary Chloride Salts as Catalysts for Methane to Hydrogen and Graphitic Powder
- University of Colorado, Boulder—Extremely Durable Concrete using Methane Decarbonization Nanofiber Co-Products with Hydrogen

Project-Level Accomplishments

During FY 2019, projects in the Hydrogen Fuel R&D portfolio made important progress in several key areas, as highlighted below.

Electrolytic Hydrogen Production

- Demonstrated faradaic efficiency >85% and electric efficiency >75% at 1 A/cm^2 with a high-temperature proton conducting electrolysis cell. (FuelCell Energy)

Biological Conversion of Hydrocarbon Feedstocks for Hydrogen Production

- Demonstrated a hydrogen production rate of 2.75 L/L-d in Clostridium thermocellum fermenting pretreated biomass in a batch bioreactor, a 24% improvement over the non-engineered strain, suggesting the simultaneous utilization of hemicellulose in the biomass. (NREL, Pacific Northwest National Laboratory [PNNL], Argonne National Laboratory [ANL], and Lawrence Berkeley National Laboratory [LBNL])

HydroGEN Accomplishments

The HydroGEN consortium fosters cross-cutting materials innovation using theory-guided applied materials R&D to advance all emerging thermochemical and electrolysis AWS pathways (LTE, HTE, PEC, and STCH), including hybridized systems. Throughout FY 2019 HydroGEN has fostered collaboration between the core national laboratories and industry and academic partners resulting in the exchange of more than 100 material samples, two Materials Research Society Symposia, 30 published papers, 104 presentations, one patent with two provisional applications filed, and one accepted SLAC National Accelerator Laboratory proposal. The consortium added three new node capabilities and updated more than 40 existing nodes to expand relevance based on seedling project needs. The following highlights are from the HydroGEN seedling projects that are leveraging HydroGEN capabilities to accelerate their materials R&D.

Low-Temperature Electrolysis Materials R&D

- Demonstrated improvement in PEM electrolysis cell performance (400 mA/cm^2 at 1.78 V) using cobalt metal organic framework (MOF)-derived platinum group metal (PGM)-free oxygen evolution catalysts (1–4 mg/cm^2) and Pt/C hydrogen evolution catalysts (0.35 mg/cm^2), Nafion membrane, 60°C. After 2,000 cycles between 1.4 V to 1.7 V, the cell voltage at 200 mA/cm^2 increased by only 25 mV. (ANL)
- Demonstrated high anion exchange membrane (AEM) electrolyzer performance (1 A/cm^2 at 1.8 V, 90°C) using PGM-free NiFeCo/Raney Ni oxygen evolution catalysts, NiMo/C hydrogen evolution catalysts, and MQN-10C AEM, enabling durable, high-performing materials for efficient and low cost hydrogen production. (Northeastern University and University of Delaware)

High-Temperature Electrolysis Materials R&D

- Improved oxygen conducting solid oxide electrolysis cell (o-SOEC) performance (>1.5 A/cm^2 at 1.2 V, 700°C) and demonstrated improved full-cell stability, with a degradation rate of <20 mV/kh over a 1,000 h durability test at 1.5 A/cm^2, 700°C, in air and 50 vol % H_2O–50 vol % H_2. (Northwestern University)

Photoelectrochemical Materials R&D

- Demonstrated successful synthesis of wide bandgap (~2 eV) chalcopyrite materials using a cost effective, solution-based approach for scalable tandem PEC cell assembly procedures. (University of Hawaii)
- Achieved a solar-to-hydrogen efficiency of 12.8% for unassisted water splitting (10.4 mA/cm^2) under 1-sun illumination. (Rutgers, the State University of New Jersey)

Solar Thermochemical Materials R&D

- Developed a high-throughput computational and combinatorial experimental approach to accelerate materials discovery, differentiating thermochemically active from merely thermal reducible compositions with a single color measurement. (Colorado School of Mines)
- Successfully utilized machine learning methods to screen more than 10^{10} potential descriptors to discover a single new descriptor based solely on chemical composition that is 92% accurate at predicting perovskite stability. (University of Colorado Boulder)

HyMARC Accomplishments

The HyMARC consortium completed activities to improve the understanding of scientific gaps impeding the advancement of solid-state storage materials. In FY 2019, HyMARC kicked off Phase 2 of its activities, having completed its 3-year Phase 1 at the end of FY 2018. With the start of Phase 2, HyMARC initiated a parallel effort in hydrogen carriers R&D that is well coordinated with its existing efforts on adsorbents and metal hydrides. This foundational R&D will facilitate interactions with the new seedling projects selected in late FY 2019 focusing on carriers. The consortium's research during FY 2019 resulted in 31 publications and 91 presentations. The following are selected highlights from the core team's R&D activities in FY 2019.

- Successfully demonstrated light-activated hydrogen desorption from two different material systems (TiN/MgH_2, $TiOx/Mg(BH_4)_2$) using LED light at ambient temperature. (NREL)
- Continued to expand characterization capabilities and upgrade or develop new equipment for several methods, including thermal conductivity; high-temperature pressure, composition, temperature (PCT); isosteric heat determination; a suite of synchrotron X-ray scattering and diffraction techniques; calorimetry; and infrared and nuclear magnetic resonance spectroscopy. (All labs)
- Completed characterization of H_2—V_2^+ sites in the MOF material V_2Cl_2.8(btdd) to confirm a $-\Delta H_{ads}$ value of 21 kJ/mol, the first material demonstrated with a binding enthalpy in the 15–25 kJ/mol range predicted to enable significant room-temperature hydrogen adsorption storage. (LBNL)

HyMARC Seedling Accomplishments

The HyMARC seedling projects are high-risk, high-reward projects that focus on material development and rely heavily on the HyMARC core national lab team for guidance to accelerate their materials development efforts through computational, synthetic, characterization, and validation capabilities. Examples of progress achieved by the HyMARC seedling projects include the following.

- Demonstrated continued improvement in reducing the temperature and pressure conditions for hydrogenation of magnesium boride. (University of Hawaii)
- Demonstrated three cycles of reversible capacity >4 wt % H_2 (hydride basis) using $NaAlH_4$ with a diglyme electrolyte operating at 150°C dehydrogenation and 75°C, 50 bar hydrogenation conditions. (Liox Power)
- Developed coated $Mg(BH_4)_2$ nanoparticles through atomic layer deposition that achieved 7.6 wt % hydrogen desorption at 200°C. (NREL)
- Synthetically controlled particle size to demonstrate an 81% improvement in the tap density of powdered MOF-5 with negligible loss in surface area. (University of Michigan)

High-Pressure Compressed and Cryogenic Hydrogen Storage

- Demonstrated >10 filament, air gap, hollow fiber spinning of lower-cost polyacrylonitrile (PAN) precursor polymer with outer diameter <100 µm and inner diameter <50 µm. Also demonstrated lower-energy solvent recovery through sorption in activated carbon modules, resulting in >19% projected cost reduction by means of low-cost polymer, water minimization, and low-energy solvent recovery. (University of Kentucky)

- Developed a new class of polymer precursors based on a graft polyethylene (PE)-g-Pitch copolymer containing PE backbone and Pitch side chains with some free Pitch molecules resulting in similar nano-polycrystalline carbon fiber morphology. (Penn State University)
- Demonstrated >15°C decrease in PAN melt temperature using ionic liquid as plasticizer. The decreased PAN melt temperature enables the melt spinning process, which indicates a potential 50% cost reduction in the production process compared to conventional wet spinning. Also demonstrated melt spinning of 30% PAN in five different ionic liquids. (Oak Ridge National Laboratory [ORNL])
- Advanced activities to evaluate cryogenic hydrogen storage applications including:
  - Completed tensile testing of epoxy at 40 K, 140 K, and 200 K. (PNNL)
  - Demonstrated a 14.7% increase in interlaminar shear strength between fibers and epoxy matrix by adding 1% TiO_2 nanoparticles. (ORNL)
  - Performed composite tank simulation to verify the composite damage. (PNNL and ANL)
  - Performed risk analysis on a 3D cryo-compressed hydrogen tank. (ANL)

Techno-Economic Analysis

The subprogram also continued carrying out techno-economic assessments of hydrogen production and storage technologies to ensure the overall portfolio is heading toward meeting DOE's ultimate goals. As referenced in the Technology Status and Accomplishments section, the Program updated its cost analysis on compressed hydrogen storage and electrolysis.

BUDGET

The FY 2019 appropriation for the Hydrogen Fuel R&D subprogram was $39 million with an additional $4 million from the Hydrogen Infrastructure R&D appropriations to support hydrogen carrier development activities, for a total subprogram budget of $43 million. The hydrogen production and storage R&D portfolios were funded at $30 million and $13 million, respectively. The hydrogen delivery portion is described in the Infrastructure and Systems R&D section of the Annual Progress Report. Figure 4 shows the budget breakdown for the Hydrogen Fuel R&D subprogram.

Funds going toward the hydrogen storage portfolio supported primarily R&D advancing hydrogen storage materials, including adsorbents and hydrogen carriers, through the HyMARC consortium and seedling projects. Funds also supported efforts to advance hydrogen storage vessels through low-cost carbon fiber precursor development and processing.

Funds going toward hydrogen production supported R&D advancing direct solar water splitting and advanced electrolysis through the HydroGEN consortium, innovative concepts, and benchmarking and analysis.

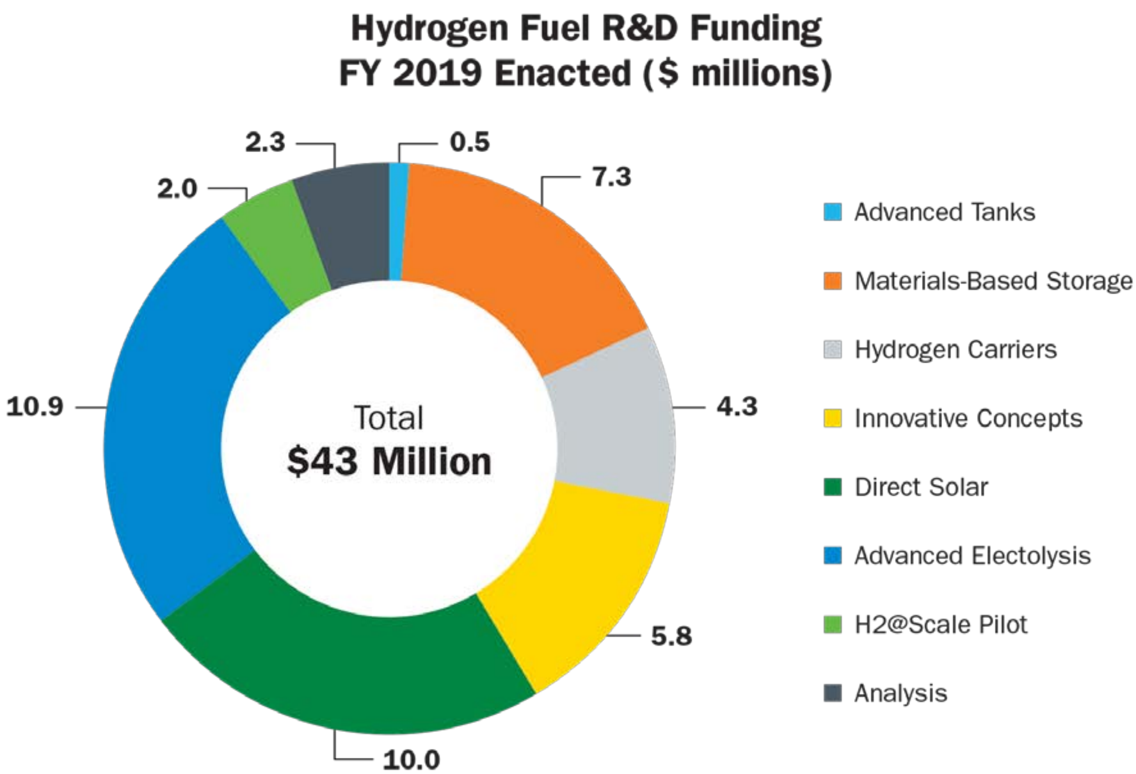

Figure 4. Hydrogen Fuel R&D subprogram FY 2019 enacted budget

Note: FY 2019 appropriation includes $4 million from Hydrogen Infrastructure R&D to support hydrogen carriers efforts.

UPCOMING ACTIVITIES AND PLANS

The Hydrogen Fuel R&D subprogram will continue efforts to maximize early-stage R&D in advanced hydrogen production and storage technologies with the potential to meet DOE's ultimate targets. In addition, the subprogram will initiate the following activities in FY 2020:

- Expand early-stage R&D in bulk storage through hydrogen carriers projects to support the H2@Scale initiative.
- Leverage collaboration with the Vehicle Technologies Office to continue R&D in materials-based storage addressing challenges for natural gas and hydrogen storage onboard medium- and heavy-duty transportation.
- Continue early-stage R&D in physical storage through innovative concepts and cost reduction approaches for carbon fiber.
- Continue support of foundational research needs in hydrogen production identified through H2@Scale efforts, including continued emphasis on research innovations for enhancing efficiency and durability and reducing costs in materials systems for all hydrogen production pathways.
- Expand early-stage R&D through the HydroGEN Advanced Water Splitting Materials consortium, including initiating Phase 3 of the 20 previously awarded seedling projects, supporting Phase 1 of the 11 new seedling projects awarded in FY 2019, and enhancing the HydroGEN national laboratory core capabilities in AWS technologies (LTE, HTE, PEC, and STCH).

- Expand emphasis on the development of robust materials-characterization protocols and performance-benchmarking standards to verify the potential of materials innovations. Begin validation of the protocols that are currently being drafted for the four AWS technology pathways.
- Continue leveraging cross-office and cross-agency R&D opportunities and resources, including expanded collaboration with the National Science Foundation, the DOE Office of Basic Energy Sciences program in solar fuels, and the Advanced Research Projects Agency–Energy.

Ned Stetson
Hydrogen Fuel R&D Program Manager
Fuel Cell Technologies Office
Office of Energy Efficiency and Renewable Energy
U.S. Department of Energy
1000 Independence Ave., SW
Washington, DC 20585-0121
Phone: 202-586-9995
Email: Ned.Stetson@ee.doe.gov