Hydrogen Technologies – 2022

Subprogram Overview

Introduction

The Hydrogen Technologies subprogram focuses on research, development, and demonstration (RD&D) to reduce the cost and improve the reliability of technologies used to produce, deliver, and store hydrogen from diverse domestic feedstocks and energy resources. Hydrogen Technologies is developing a set of hydrogen production, delivery, and storage technology pathways in support of RD&D needs identified through the U.S. Department of Energy's (DOE) H2@Scale efforts and the Infrastructure Investment and Jobs Act (also known as the Bipartisan Infrastructure Law [BIL]). The subprogram addresses technical challenges through a portfolio of projects in three RD&D categories:

- Hydrogen Production addresses low-cost, highly efficient, clean hydrogen production technologies that use diverse sustainable domestic sources of energy and feedstocks. RD&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) and the Hydrogen from Next-generation Electrolyzers of Water consortium (H2NEW) to accelerate RD&D of advanced water-splitting technologies for clean, sustainable hydrogen production.
- Hydrogen Infrastructure addresses low-cost, high-efficiency technologies to move hydrogen from the point of production to the point of use. RD&D activities investigate liquefaction, pipelines, chemical carriers, and tube trailers to transport hydrogen over long distances, as well as compressors, pumps, dispensers, and auxiliary components to support the development of hydrogen stations serving medium- and heavy-duty fuel cell electric vehicles. The Hydrogen Materials Compatibility Consortium (H-Mat) coordinates RD&D on accelerated test methods and novel, low-cost, durable metals and polymers for use in hydrogen infrastructure. The HyBlend effort investigates the potential of blending hydrogen into the natural gas infrastructure.
- Hydrogen Storage addresses cost-effective onboard and off-board hydrogen storage technologies with improved energy density and lower costs. RD&D activities investigate high-pressure compressed storage, cryogenic liquid storage, materials-based storage, and hydrogen carriers. Activities in the latter two topic areas are coordinated through the Hydrogen Materials–Advanced Research Consortium (HyMARC) to accelerate the discovery and development of breakthrough hydrogen storage materials.

Since the Fiscal Year (FY) 2021 Annual Merit Review, the BIL has been enacted. The law includes a provision for clean hydrogen electrolysis for production of clean, low-carbon hydrogen. With this provision, all of the electrolysis activities under the Hydrogen Production category are being shifted under the BIL. The Hydrogen Production funding from annual appropriations will focus on non-electrolysis technologies at lower technology readiness levels (TRLs), such as photoelectrochemical, solar thermochemical, and biological hydrogen production processes. Key activities kicked off in the past year for the Hydrogen Infrastructure and Hydrogen Storage categories include the HyBlend effort on hydrogen–natural gas blending, four projects on low-cost carbon fiber (CF) for high-pressure tanks, and an ultra-large-scale liquid hydrogen (LH2) storage vessel project.

Goals

The Hydrogen Technologies subprogram aims to develop technologies so that clean, low-carbon hydrogen can be competitive with incumbent and emerging technologies across diverse applications. These applications include transportation, power generation, energy storage, and industrial and chemical processes. Specific subprogram objectives include the following:

- Develop low-cost, sustainable, and low-carbon hydrogen production technologies with the potential to meet an intermediate hydrogen production cost target of \$2/kg H_2 by 2026 and \$1/kg H_2 by 2031 (the Hydrogen Shot target).
- Develop hydrogen infrastructure technologies, including hydrogen delivery, storage, and dispensing, with the aim of meeting overall cost targets for delivered and dispensed hydrogen. For vehicle refueling, there is

an intermediate cost target of \$5/kg H_2 and an ultimate cost target of \$2/kg H_2 for delivery and dispensing, resulting in a total intermediate cost (production plus delivery/dispensing) of \$7/kg H_2 and an ultimate cost of \$3–\$4/kg H_2 dispensed to vehicles.

- Develop low-cost, efficient, compact, and safe hydrogen storage technologies for use with end-use applications, including on board vehicles and at end-use sites. For vehicles, the objective includes meeting an intermediate cost target of \$9/kWh (\$300/kg H_2 stored) by 2030 and ultimately \$8/kWh (\$266/kg H_2 stored) for Class 8 long-haul tractor–trailers.

Key Milestones

The Hydrogen Technologies subprogram has key milestones for each of the technology areas:

- Develop clean hydrogen production technologies able to meet cost targets of \$2/kg H_2 by 2026 and \$1/kg H_2 by 2031.
- Develop polymer electrolyte membrane (PEM) electrolyzer technologies with stack targets of ≥70% electrical efficiency, ≤\$100/kW, and a lifetime of ≥80,000 hours by 2026; and develop stacks using oxide-ion-conducting solid oxide electrolysis cells (O^{2-} SOECs) with ≥ 98% electrical efficiency, ≤ \$100/kW and a lifetime of ≥ 60,000 hours by 2026.
- Develop hydrogen infrastructure technologies for medium- and heavy-duty vehicle refueling to meet an intermediate delivery and dispensing cost target of ≤\$5/kg H_2 and an ultimate cost target of ≤\$2/kg H_2.
- Develop medium- and heavy-duty vehicle hydrogen refueling technologies capable of dispensing either 700 bar compressed or LH2 at an average rate of 10 kg H_2/minute, with a peak rate of ≤18 kg H_2/minute.
- Develop onboard hydrogen storage technologies meeting an intermediate cost target of \$9/kWh (\$300/kg H_2 stored) by 2030 and ultimately \$8/kWh (\$266/kg H_2 stored) for Class 8 long-haul tractor–trailers.
- Develop onboard hydrogen storage systems for Class 8 long-haul tractor–trailers capable of at least a 5,000-cycle life, with pressurized system components capable of at least 11,000 cycles.

FY 2022 Technology Status and Accomplishments

Production

- Documented in a Program Record that the clean hydrogen production cost with current PEM electrolyzer technology can be less than \$4/kg H_2 in regionally specific cases.
- Developed a thin (50 µm) PEM membrane with an integrated gas recombination layer specific to electrolyzer technology that is compatible for roll-to-roll fabrication processes.
- Used a combination of experimental, modeling, and analysis techniques to achieve important advances in the understanding of Ir dissolution, which has significant impacts on the cost and degradation of PEM electrolysis.
- Demonstrated 20% solar-to-hydrogen in a hydrophobic perovskite photoelectrochemical cell with a Pt/graphite barrier lifetime of 100 hours.
- Used computational modeling to guide selection of promising high-entropy perovskite oxides for solar thermochemical hydrogen production; synthesized and characterized over 150 compositions and demonstrated production of >400 µmol H_2/g perovskite.
- Collaborated with the National Renewable Energy Laboratory (NREL) and Pacific Northwest National Laboratory to host workshops on liquid alkaline electrolyzers, advanced materials for PEM electrolyzers, and high-temperature electrolyzer manufacturing.
- Demonstrated 90% Faradaic efficiency for a proton-conducting SOEC operating at commercially relevant conditions (1.0 A/cm^2, 600°C, 70% steam), with stable operation over 5,000 hours.

Infrastructure

- Completed commissioning of a high-flow hydrogen fueling system at the NREL Energy Systems Integration Facility and achieved a 76 kg fill in under six minutes, as determined by conducting a test representative of fueling a heavy-duty vehicle. This test had an average flow rate of nearly 13 kg/minute and a peak rate of over 23 kg/minute.
- Initiated validation efforts for the publicly accessible H2FillS model with high-flow test data up to approximately 80 MPa. The model allows users to simulate the impact of varying fueling methods on the thermodynamics of fueling equipment and onboard hydrogen storage.
- Demonstrated accelerated techniques to characterize the life of materials in hydrogen twice as fast as traditional approaches.
- Demonstrated high-throughput techniques to test thin film metals in hydrogen.
- Completed a technical report summarizing ASME and National Fire Protection Agency codes and standards relevant to hydrogen blending in pipelines.

Storage

- Hosted multiple workshops, including two focusing on LH2 storage (in collaboration with NASA) and one focusing on bulk gaseous hydrogen storage (in collaboration with the DOE Office of Fossil Energy and Carbon Management).
- Developed several design concepts for the world's largest LH2 storage tank and down-selected to two concepts for detailed evaluation.
- Demonstrated high-pressure hydrogen release from hydrogen carriers—formic acid and formic acid–methanol blends—with capacities as high as 5.3 wt % and good catalyst stability.
- Showed a 75% increase in volumetric capacity for a composite of a porous cage and metal–organic framework (MOF) compared to the MOF alone. A significant increase in packing density allowed for the increased capacity without sacrificing adsorption behavior.

New Project Selections

Funding Opportunity Announcement DE-FOA-0002446

Production

- Nextech Materials, Ltd.: Low-Cost Manufacturing of High-Temperature Electrolysis Stacks
- Cummins Inc.: Automation of Solid Oxide Electrolyzer Cell and Stack Assembly
- Southern Company Services, Inc.: Novel Microbial Electrolysis System for Conversion of Biowastes into Low-Cost Renewable Hydrogen
- Pennsylvania State University: Novel Microbial Electrolysis Cell Design for Efficient Hydrogen Generation from Wastewaters
- Strategic Analysis, Inc.: Hydrogen Production Cost and Performance Analysis

Infrastructure

- Czero, Inc.: Advanced High-Throughput Compression System for Medium- and Heavy-Duty Transportation
- Gas Technology Institute: Cost-Effective Pre-Cooling for High-Flow Hydrogen Fueling
- Nikola Corporation: Autonomous Fueling System for Heavy-Duty Fuel Cell Electric Trucks

Storage

- Strategic Analysis, Inc.: Hydrogen Storage Cost and Performance Analysis

Technology Commercialization Fund

Production

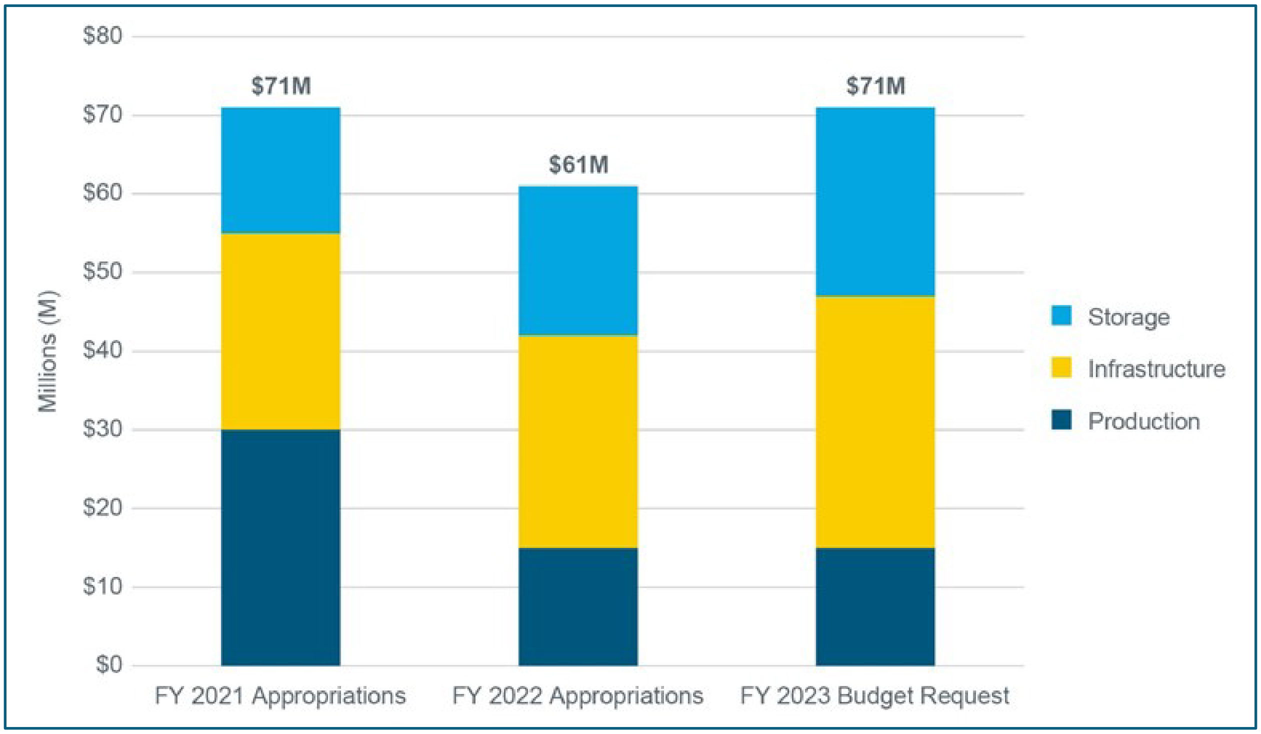
- Sandia National Laboratories and Giner, Inc.: Alkaline Water Electrolysis
- Lawrence Berkeley National Laboratory, Nel Hydrogen, and De Nora Tech., Inc.: Porous Transport Electrodes for Proton Exchange Membrane Electrolyzers
- NREL and Eaton Corporation: Hydrogen-based Power grid support using ElectrolyzeRs with Value stacking (HYPER-V)

Storage

- NREL and Honeywell Aerospace: FueL Additives for Solid Hydrogen (FLASH) Carriers for Electric Aviation
- Los Alamos National Laboratory and Oberon, Inc.: Dimethyl Ether as a Renewable Hydrogen Carrier: An Innovative Approach to Renewable Hydrogen Production

Budget

Enacted on November 15, 2021, the BIL includes the Clean Hydrogen Electrolysis Program, with $1 billion of new funding. As noted above, electrolysis-related activities were shifted to BIL funding, so the Hydrogen Production category's budget was reduced from $30 million in FY 2021 to $15 million in FY 2022. For Hydrogen Infrastructure, the budget was increased from $25 million to $27 million, and for Hydrogen Storage, the budget was increased from $16 million to $19 million.



Project Summaries

Below are brief Hydrogen Technologies project summaries of oral presentations given during the 2022 Annual Merit Review. The full list of projects, including oral and poster presentations, is provided in Appendix D.

Project #P-148: HydroGEN Overview: A Consortium on Advanced Water-Splitting Materials

Huyen Dinh, National Renewable Energy Laboratory

DOE Contract #	WBS 2.7.0.518 and 2.7.0.513
Start and End Dates	6/1/2016
Partners/Collaborators	• HydroGEN Consortium

Project Goal and Brief Summary

The HydroGEN consortium's objective is to facilitate collaborations between federal laboratories, academia, and industry to evaluate and accelerate R&D of innovative advanced materials that are critical and necessary to advanced water-splitting technologies for clean, sustainable, and low-cost hydrogen production. Water-splitting technology pathways supported by HydroGEN include photoelectrochemical, solar thermochemical, low-temperature electrolysis, and high-temperature electrolysis. In addition to collaborating with industry and academia, HydroGEN uses a synergetic, multi-laboratory approach, utilizing and integrating the labs' world-class capabilities to address the critical research gaps identified by the lab teams and HydroGEN benchmarking and protocol workshops in each of the advanced water-splitting technologies.

Project #P-196: H2NEW Consortium: Hydrogen from Next-Generation Electrolyzers of Water

Bryan Pivovar, National Renewable Energy Laboratory, and Richard Boardman, Idaho National Laboratory

DOE Contract #	WBS 2.7.0.519 and WBS 2.7.0.1003
Start and End Dates	10/1/2020
Partners/Collaborators	• National Renewable Energy Laboratory • Idaho National Laboratory • Argonne National Laboratory • Pacific Northwest National Laboratory • Lawrence Berkeley National Laboratory • Los Alamos National Laboratory • Lawrence Livermore National Laboratory • Oak Ridge National Laboratory • National Energy Technology Laboratory • National Institute of Standards and Technology

Project Goal and Brief Summary

The H2NEW consortium is a comprehensive, concerted effort focused on overcoming technical barriers to enable affordable, reliable, and efficient electrolyzers that can achieve <$2/kg H_2 by 2025. H2NEW is studying both low-temperature electrolysis, based on an acidic PEM, and high-temperature electrolysis, based on oxide-ion-conducting solid electrolyte. The core H2NEW national laboratory team is addressing components, materials integration, and manufacturing R&D. The team is working to improve scientific understanding of the performance, cost, and durability tradeoffs in electrolysis systems, including under predicted future dynamic operating modes, by using a combination of experimental, analytical, and modeling tools.

Project #P-197: Advanced Manufacturing Processes for Gigawatt-Scale Proton Exchange Membrane Water Electrolyzers: Oxygen Evolution Reaction Catalysts and Electrodes

Andy Steinbach, 3M

DOE Contract #	DE-EE0009237
Start and End Dates	1/1/2021–3/30/2024
Partners/Collaborators	• Giner, Inc. • Plug Power Inc. • National Renewable Energy Laboratory • Oak Ridge National Laboratory

Project Goal and Brief Summary

This project aims to develop manufacturing processes for reproducible and uniform PEM water electrolysis components at commercial scale, specifically for an oxygen evolution reaction catalyst, electrode, and thrifted catalyst-coated membranes. Once developed, these processes will be scaled up to gigawatts per year, and component production will begin. The produced components will then be assessed and validated for efficiency, durability, power density, and low iridium content in megawatt-capable stacks relevant for gigawatts-per-year deployment scale. If successful, this project's results will help satisfy industry needs for high-volume capacity PEM electrolysis and reduced manufacturing costs for the necessary components.

Project #P-198: Enabling Low-Cost Proton Exchange Membrane Electrolysis at Scale Through Optimization of Transport Components and Electrode Interfaces

Christopher Capuano, Nel Hydrogen

DOE Contract #	DE-EE0009238
Start and End Dates	10/1/2020–9/30/2023
Partners/Collaborators	• National Renewable Energy Laboratory • Oak Ridge National Laboratory • De Nora • University of California, Irvine

Project Goal and Brief Summary

This project aims to develop an optimized porous transport layer (PTL) designed for an electrolyzer system and upscaled to manufacturing level. The PTL serves many purposes: the distribution of water flow across the cell, the removal of gaseous oxygen from the anode, the establishment of contact between the anode and current collector, and the provision of mechanical support for the membrane. At present, available PTL materials are adapted from other industries' materials and not optimized for electrolysis. The addition of a microporous layer to the existing design will provide a more closely packed pore structure immediately adjacent to the catalyst layer, balancing porosity with contact area. Porosity will also be balanced against mechanical strength to support hydrogen pressure. These improvements will enable good fluid management while providing a uniform interface to the catalyst and membrane. The PTL will enable integration of advanced membrane electrode assemblies in service of advancing electrolyzers toward the DOE cost goal of $2/kg.

Project #P-199: Integrated Membrane Anode Assembly and Scale-Up

Monjid Hamdan, Plug Power Inc.

DOE Contract #	DE-EE0009236
Start and End Dates	8/1/2021–7/31/2024
Partners/Collaborators	• University of Tennessee • Colorado School of Mines • Oak Ridge National Laboratory • National Renewable Energy Laboratory

Project Goal and Brief Summary

This project will develop and fabricate a single-piece, integrated membrane anode assembly with the aim of reducing electrolyzer capital costs. The status quo involves a time-consuming manufacturing process and expensive components. This project will implement innovative manufacturing processes and architectures to reduce the cost and fabrication time of the anode support structure and membrane electrode assembly, the most expensive components in an electrolyzer stack. Researchers will create a single-piece anode support structure and catalytic and ionomeric coatings. The coatings will be applied to the anode support structure's surface to form the integrated membrane anode assembly. The project will then scale up and demonstrate the production process.

Project #IN-015: Optimizing the Heisenberg Vortex Tube for Hydrogen Cooling

Jacob Leachman, Washington State University

DOE Contract #	DE-EE0008429
Start and End Dates	1/23/2019–6/30/2023
Partners/Collaborators	• Plug Power Inc.

Project Goal and Brief Summary

This project aims to establish that Washington State University's Heisenberg Vortex Tube cooling system can achieve the following improvements to cryogenic hydrogen storage systems: (1) a 20% increase in LH2 pump volumetric efficiency through vapor separation and subcooling, (2) a 20% decrease in LH2 storage tank boil-off losses through thermal vapor shielding, and (3) an increase of supercritical hydrogen expansion from 31% to more than 40% through greater isentropic efficiency.

Project #IN-016: Free-Piston Expander for Hydrogen Cooling

Devin Halliday, Gas Technology Institute

DOE Contract #	DE-EE0008431
Start and End Dates	1/1/2019–12/31/2022
Partners/Collaborators	• Center for Electromechanics (University of Texas at Austin) • Argonne National Laboratory

Project Goal and Brief Summary

The project team is developing a free-piston linear motor expander that can conduct hydrogen pre-cooling for light-duty hydrogen fueling while producing energy that can be used to offset compressor energy consumption. Pre-cooling units represent 10% of the capital cost of hydrogen fueling stations and impose significant operating costs as well. Replacing conventional pre-cooling units with expanders could reduce these costs, removing a major barrier to hydrogen fuel cell vehicle adoption.

Project #IN-034: HyBlend: Pipeline Cooperative Research and Development Agreement – Cost and Emissions Analysis

Mark Chung, National Renewable Energy Laboratory; Amgad Elgowainy, Argonne National Laboratory

DOE Contract #	8.6.2.1
Start and End Dates	10/1/2021–9/31/2023
Partners/Collaborators	• Sandia National Laboratories • Pacific Northwest National Laboratory

Project Goal and Brief Summary

This project will develop tools to quantify the economic and environmental impacts of blending hydrogen into U.S. natural gas pipelines. Existing national laboratory tools (e.g., the Hydrogen Analysis model) will be leveraged to estimate—and quantify—the value proposition, with the goal of accelerating early-market hydrogen technology adoption and short-term emissions reduction. Scenarios will be designed to evaluate the application of hydrogen blending across different sections of the U.S. natural gas pipeline system, helping to provide pipeline operators with a pathway to converting existing assets into clean infrastructure.

Project #IN-035: HyBlend: Pipeline Cooperative Research and Development Agreement – Materials Research and Development

Kevin Simmons, Pacific Northwest National Laboratory; Chris San Marchi, Sandia National Laboratories

DOE Contract #	8.6.4.2
Start and End Dates	10/1/2021–9/31/2023
Partners/Collaborators	• Argonne National Laboratory • National Renewable Energy Laboratory

Project Goal and Brief Summary

This project aims to provide a scientific basis for the assertion of pipeline safety for hydrogen service. More specifically, the project aims to develop a scientific understanding of variables and mechanisms that contribute to hydrogen-induced degradation of piping and pipeline materials. National lab capabilities will be leveraged to examine materials performance in hydrogen environments, and the project will design probabilistic analysis tools to quantify the structural integrity of pipeline networks for hydrogen service. Converting networks for hydrogen blending within the natural gas pipeline system may offer a low-cost pathway to distribute clean hydrogen, and the data gathered for this project will help ensure the safety of decarbonized energy infrastructure for both transitional and long-term strategies of hydrogen conveyance.

Project #ST-236: Low-Cost, High-Performance Carbon Fiber for Compressed Natural Gas Storage Tanks

Xiaodong "Chris" Li, University of Virginia

DOE Contract #	DE-EE0009239
Start and End Dates	10/1/2021–9/30/2026
Partners/Collaborators	• Oak Ridge National Laboratory • Savannah River National Laboratory • Cytec Engineered Materials (Solvay) • Hexagon R&D LLC

Project Goal and Brief Summary

This project seeks to develop and validate methods for scalable production of low-cost, high-performance CF that can be used in the manufacture of compressed natural gas (CNG) storage tanks. Researchers will incorporate the CF into the design of a low-cost, lightweight composite CNG storage tank, ensuring that it meets American National Standards Institute (ANSI) standards for CNG containers, and establish a methodology to scale up tank manufacture. The improved design and use of low-cost CF is expected to reduce the cost of conventional fiber-wound CNG storage tanks by as much as 37%.

Project #ST-237: Carbon Composite Optimization Reducing Tank Cost

Dylan Winter, Hexagon R&D LLC

DOE Contract #	DE-EE0009240
Start and End Dates	10/1/2021–9/30/2026
Partners/Collaborators	• Cytec Engineered Materials (Solvay) • Oak Ridge National Laboratory • Pacific Northwest National Laboratory • Newhouse Technology • Kenworth R&D

Project Goal and Brief Summary

Currently, the cost of gas storage tanks is a significant barrier to the mass deployment of cleaner vehicle fuel sources such as hydrogen and CNG, and CF accounts for approximately half of the total hydrogen storage system cost. This project aims to reduce compressed hydrogen and CNG storage costs by developing new and optimized technologies to produce low-cost, high-strength CF with a demonstrated cost of less than $15/kg, tensile strength of 700 ksi, and tensile modulus of 35 Msi. CF technology will be enhanced through controlled fiber morphology using tuned polymer molecular structures and optimal spinning and carbonization conditions. Researchers will use high-throughput fiber manufacturing to increase production capacity, materials characterization to minimize defects, high-performance resin and interfacial engineering to enhance the composite, and modeling to improve pressure vessel design. The project also addresses environmental concerns by exploring new methods to recover resin and fibers for secondary use.

Project #ST-238: Low-Cost, High-Strength Hollow Carbon Fiber for Compressed Gas Storage Tanks

Matthew C. Weisenberger, University of Kentucky Center for Applied Energy Research

DOE Contract #	DE-EE0009241
Start and End Dates	10/1/2021–9/30/2026
Partners/Collaborators	• Solvay Composite Materials • Steelhead Composites, Inc. • Oak Ridge National Laboratory • Advanced Fiber Technologies, Inc. • Strategic Analysis, Inc.

Project Goal and Brief Summary

This project aims to develop hollow carbon fiber (HCF) with a cost target of \$13–\$15/kg, approximately a \$10 reduction of the current cost per kilogram. Removing the fiber core increases the fiber's specific properties while maintaining tensile strength, as a disordered core contributes little to its integrity. In addition, HCF may oxidize quickly, as the reaction happens at both the interior and exterior. The development process will include advancements in fiber spinning and scale-up, as well as tailored oxidation profiling and accelerants for fast oxidation. Researchers will systematically down-select time–temperature–strain paths through low- and high-temperature carbonizations to maximize HCF strength and carbonization line speed, matching increases in oxidation line speed. Alternative uses for end-of-life tanks, as well as recycling, will be explored to determine the most cost-efficient and sustainable options. Sufficient HFC will be produced to fabricate composite overwrapped pressure vessels (COPVs) for testing. Researchers will conduct life cycle cost analyses of HCF, from manufacturing through COPV end-of-life.

Project #ST-239: Melt-Spun Polyacrylonitrile Precursor for Cost-Effective Carbon Fibers in High-Pressure Compressed Gas Tankage

Felix Paulauskas, Oak Ridge National Laboratory

DOE Contract #	DE-EE0009242
Start and End Dates	10/15/2021–9/30/2026
Partners/Collaborators	• Collaborative Composites Solutions • Virginia Tech • JR Automation • High Energy Sales LLC • Hexagon R&D LLC, Prescott Composites

Project Goal and Brief Summary

CF accounts for nearly 50% of total vehicle high-pressure storage system costs. Currently, high-tensile-strength CF is produced exclusively from polyacrylonitrile (PAN) precursor made via solution spinning, which requires extensive capital investment for fiber formation and solvent recovery. In comparison, melt-spinning of PAN offers significant advantages: reduced solvent and energy use, faster line speeds, fewer defects, and a much smaller spinning equipment footprint. This project aims to demonstrate that melt-spun PAN precursor can reduce 700 ksi CF cost by 25% of the cost of conventional solution spinning. The project will also show that the process can effectively scale to the pre-production levels necessary to make finished CF, which will then be validated in multiple high-pressure tanks. Commercialization of the resultant technology for producing cost-effective CF is a long-term goal of partner company, Prescott Composites.

Project #ST-240: Cost-Optimized Structural Carbon Fiber for Hydrogen Storage Tanks

Amit Naskar, Oak Ridge National Laboratory

DOE Contract #	4.3.0.605
Start and End Dates	4/1/2021–3/31/2024
Partners/Collaborators	• Pacific Northwest National Laboratory • 4XGroup LLC

Project Goal and Brief Summary

This project aims to manufacture low-cost, high-strength CF costing less than $15/kg, delivering target 700 ksi tensile strength and 33 Msi tensile modulus. Currently, both precursor fiber and conversion processes contribute to high CF costs, so the project aims to employ both novel precursor and new high-performance processing technologies to manufacture low-cost, high-strength CF. Researchers will conduct foundational research to enhance processability of newly synthesized PAN-based precursors. In parallel, both conventional and advanced plasma-based processing technologies will be studied for cost and performance optimization. The project will also conduct analyses to optimize tank design. Cost reductions in CF manufacture will lead to higher utilization of hydrogen in vehicles.

Project #ST-241: First Demonstration of a Commercial-Scale Liquid Hydrogen Storage Tank Design for International Trade Applications

Jo-Tsu Liao, Shell International Exploration and Production, Inc.

DOE Contract #	DE-EE0009387
Start and End Dates	9/1/2021–8/31/2024
Partners/Collaborators	• CB&I Storage Solutions LLC • GenH2 Corporation • NASA Kennedy Space Center • University of Houston

Project Goal and Brief Summary

One of three priorities in the Program is low-cost, efficient, and safe hydrogen delivery and storage. This project aims to develop a first-of-its-kind affordable, very large-scale LH2 storage tank for international trade applications, primarily for installation at import and export terminals. The project aims to create a large-scale tank design that can be used in the 20,000–100,000 m^3 range (1,400–7,100 metric tons of LH2). Key success criteria for the large-scale design include a targeted LH2 boiloff rate of less than 0.1%/day and a capital investment below 150% of liquefied natural gas storage cost. The project will also ensure that the technology meets safety and integrity regulations, codes, and standards.

Annual Merit Review of the Hydrogen Technologies Subprogram

Summary of Hydrogen Technologies Subprogram Reviewer Comments

This section provides a summary of the reviewers' remarks. The content reflects those inputs only and not the views of Program management. The complete set of review comments received is provided as Appendix A.

Hydrogen Shot Goal

The Hydrogen Shot goal of $1/kg hydrogen by 2030 is clear, well-aligned and -formulated, concise, appropriately ambitious, and aggressive, while also being tremendously challenging. The intermediate goals, e.g., $2/kg by 2026, make the Hydrogen Shot goal more manageable, and the goal makes sense given the current TRL of hydrogen production technology. However, some reviewers suggested that the Hydrogen Shot goal is more aggressive than necessary. Being able to meet the goal will depend on electricity cost, which is outside the Program's control, and specific articulated pathways to achieve the goal have not yet been identified. It would be useful to develop tools for quantifying and communicating progress toward the Hydrogen Shot goal, such as a total cost of ownership/techno-economic analysis model and dashboards.

Strategy, Targets, and Metrics

The Program has developed a comprehensive strategy on a national scale to achieve the Hydrogen Shot goal, including R&D, demonstration, deployment, education, and outreach. The Hydrogen Technologies subprogram has clearly defined targets, a clear mission and strategy, and a logical and effective organization. One reviewer, however, noted a mismatch between the stated materials and performance goals of industry and those of the national laboratories. Suggestions include:

- Adding more detailed metrics and targets at the component level, using multiple parameters, similar to the fuel cell targets.
- Measuring the success of the subprogram's activities against a metric describing how much they accelerate the hydrogen industry rather than the degree to which the subprogram's technologies are adopted by industry.
- Developing strategies for maintaining reliable energy supply during the transition to hydrogen and, in the longer term, with dependence on fewer energy sources.

Hydrogen Technologies Subprogram Portfolio

The Hydrogen Technologies subprogram's portfolio of projects is appropriately balanced across research areas to help achieve its mission and goals. It has an appropriate balance between near-, mid-, and long-term R&D and a good balance of TRLs. The following recommendations are applicable across the Hydrogen Technologies subprogram's portfolio:

- Prioritize the use of domestic materials in projects funded by the subprogram, and consider the projects' impacts on the domestic supply chain.
- Concentrate resources in the next three to five years to address critical barriers on hydrogen production, storage, transport, and fueling infrastructure to achieve the 2026 hydrogen cost target.
- Conduct component analysis to develop component-level metrics.
- Quantify performance tradeoffs for the technologies being developed within the subprogram.
- Determine which legacy projects within the subprogram were most successful and identify their most critical elements.
- Prioritize the use of safe, secure, economical, and reliable sources of materials.
- Increase the amount of research conducted on near-term, high-TRL technologies without reducing the amount of research on mid- and long-term, lower-TRL technologies.
- Critically evaluate projects to be funded through the BIL for their ability to accelerate industry's implementation of large-scale hydrogen production, distribution, and use.

In the Hydrogen Production category, reviewers commended the subprogram for adding alkaline and anion exchange membrane electrolyzers to the portfolio. Reviewers confirmed that R&D of the following topics remains necessary:

- Both basic and applied electrolyzer R&D
- Assessment of trade-offs between performance and durability for electrolyzers from a deployed system capital expenditure perspective

- R&D on platinum-group-metal (PGM) catalysts for PEM electrolysis, as well as R&D to enable thinner PEMs with lower hydrogen crossover and higher mechanical strength, R&D on PTLs, and identification of optimal material properties for PEM electrolysis
- Expanded R&D on alkaline electrolyzers, including development of thinner separators
- R&D on balance of plant to improve efficiency
- R&D on biomass/waste pathways
- Materials development for stable Ir-based catalysts at low loadings
- Advanced characterization, modeling, baselining, and focused materials development to enable electrolyzer operation at current density of 5 A/cm^2 or higher
- Accelerated R&D on anion exchange membrane electrolyzers, including durable ionomers
- Continued early-stage R&D in areas such as proton-conducting SOECs.

The Program is encouraged to use new funding through the BIL for new applied projects in key electrolyzer components and system concepts, including investment in high-TRL electrolyzers that can move beyond R&D to process development and scale-up to reduce capital costs. While one reviewer questioned whether there is sufficient benefit to warrant continued research into fossil-fuel-based hydrogen production, another cautioned the Program not to penalize “gray” hydrogen. Similarly, there were conflicting opinions regarding the appropriate amount of R&D on non-PGM catalysts for electrolysis to include in the portfolio. Individual reviewers made the following remarks for consideration:

- The major Chinese electrolyzer manufacturers could be benchmarked as a measure of U.S. competitiveness in the electrolyzer market.
- Universities are underfunded relative to the national laboratories, despite their advantages in tackling certain fundamental issues.
- Funding should be more equitably distributed between low-temperature and high-temperature electrolysis.

In addition to research needs, individual reviewers had suggestions regarding hydrogen production analysis needs:

- The electricity cost assumption used in the electrolysis analyses is too low and should include transmission and distribution costs.
- The entire value chain should be analyzed to ensure viable goals and accurate cost status, including buffering costs when hydrogen is made from intermittent electricity sources yet downstream users require uninterrupted feed for continuous operations.
- The war in Ukraine and the drought conditions and scarcity of water have impacts on hydrogen analyses.

Additional recommendations related to the Hydrogen Production portfolio include implementing a prize where the award is a federal fleet off-take agreement for the first organization to demonstrate $1/kg production with a hydrogen price that can compete with conventional fuel; implementing seed programs for high-risk, high-reward research; and focusing on supply chain development.

In the Hydrogen Infrastructure category, reviewers recommended analysis of the integration of renewable power, grid capacity, and hydrogen production at the point of use to understand how to minimize transport of hydrogen. R&D and materials testing for hydrogen pipelines should accelerate. Small engineered underground hydrogen storage, LH2 storage, liquefaction technology, fueling interfaces for LH2, and transport and distribution of hydrogen are underrepresented in the Hydrogen Technologies subprogram portfolio.

In the Hydrogen Storage category, reviewers identified the need for accelerated development of hydrogen storage technologies, liquid carriers, and materials for high-pressure tanks. Also needed are new approaches to reducing the cost of CF for fiber-reinforced tanks. One suggestion is a joint materials discovery program for high-strength materials for high-pressure tanks; the co-sponsors would be the Office of Energy Efficiency and Renewable Energy and the Office of Basic Energy Sciences. One reviewer cautioned against de-emphasizing hydrogen storage and carriers in light of the focus on meeting the Hydrogen Shot goal. Another reviewer suggested that successful development of solid-state hydrogen storage would warrant the investment.

Challenges

While some reviewers felt the challenges to the Program goals were well-articulated and plans were adequately formulated, others felt more discussion of barriers, assessment of risks to overcome barriers, and definition and prioritization of the challenges would be useful. The Program could address the specifics of the R&D steps to achieve the goals, present a detailed pathway for achieving the progression of TRLs, and illustrate the relative TRL and manufacturing readiness level of its accomplishments. More discussion of quantifying and controlling emissions from hydrogen projects would be welcome; there is a need to identify the challenges in overcoming the energy and greenhouse gases involved in producing hydrogen at large scales. According to one reviewer, hydrogen storage remains a critical issue and should receive more attention at the Annual Merit Review.

Another challenge is the lack of a clear pathway to unsubsidized renewable energy to produce hydrogen at $1/kg. There was no mention of the significant materials-related infrastructure that is needed to meet the goals. It was not clear that the targets address return on investment and operating costs. One reviewer observed insufficient involvement and support for (1) the smooth transition of energy technologies without significant disruption and (2) economic and secure supply chains that benefit all stakeholders. There is a need for improved and increased coordination with stakeholders, industry, communities, supply chains, and others.

Clean Hydrogen Electrolysis Program

The Clean Hydrogen Electrolysis Program has well-thought-out and well-articulated plans. One reviewer recommended more strongly favoring advanced concepts to improve the chances of meeting the Hydrogen Shot goal; another recommended increasing the emphasis on hydrogen compression to improve system-level reliability for the electrolysis program.

Consortia

As noted in the Hydrogen Program Overview, reviewers praised the Program's consortia approach for its efficiency, innovation, and success and encouraged the Program to enhance the visibility of its consortia, while cautioning that care must be taken to avoid management and coordination challenges. Industry engagement with the HydroGEN and H2NEW consortia is important; such collaboration would help advance electrolyzer technology to meet the Program's goals. HydroGEN is an extremely effective consortia model, though one reviewer felt that some of the lab node collaborations in HydroGEN are not very effective and recommended development of a clear set of metrics for evaluation and feedback of the lab nodes program. Although HydroGEN's important work should continue, it is unlikely to contribute to achievement of the Hydrogen Shot goal; perhaps the consortium's research focuses should be reconsidered. H2NEW has "unparalleled technical understanding and capabilities" (to quote one reviewer), although technical efforts within H2NEW and HydroGEN seem to overlap.

The HyMARC consortium was not discussed in detail during the Annual Merit Review. It was unclear whether the consortium's research priorities have changed or any of its research directions have been or will be discontinued. One reviewer remarked that HyMARC continues to focus on material evaluation to meet long-term goals for low cost and high volumetric and gravimetric efficiencies, while another commented that it is difficult to see a clear path to any material that will meet the goals. One reviewer recommended that HyMARC consider developing specific hydrogen storage materials for the less challenging applications beyond passenger vehicles, including one-way hydrogen storage materials for hydrogen cartridges.

International

The International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) provides a vehicle for U.S. experts to participate in development of an international low-carbon or renewable hydrogen standard, addressing the need for alignment and standardization of clean hydrogen production and distribution evaluation methods, metrics, targets, and implementation. Verifiable, trusted, certified, and consistent hydrogen life cycle performance is needed, as well as international alignment on strategies and use cases for support of or preference for certain hydrogen distribution and use life cycles, especially concerning methods of transport, distribution, and hydrogen delivery. Also needed are more standard methods and terminology related to environmental performance and the engineering and technology language used. The Program is encouraged to share and spread the consortia approach in other countries to create bridges and to leverage electrolysis progress and knowledge outside the United States through international collaboration.