Infrastructure and Systems R&D Overview

INTRODUCTION

The Infrastructure and Systems Research and Development (R&D) subprogram[1] aims to address technology barriers, systems and systems-integration challenges, and other cross-cutting activities to enable H2@Scale. The subprogram includes three project categories: Hydrogen Infrastructure R&D, Technology Acceleration, and Systems Analysis. The Infrastructure and Systems R&D subprogram areas in 2019 included (1) low-cost, high-efficiency liquefaction, pipelines, chemical carriers, and tube trailers; (2) low-cost and reliable compressors, pumps, dispensers, and stationary storage; (3) grid integration of hydrogen production; (4) novel methods of manufacturing and improvements in durability of hydrogen technologies; and (5) systems analysis to inform R&D priorities and determine the impact. Techno-economic analysis is used to identify drivers of hydrogen cost and barriers to large-scale growth, which inform Program planning and portfolio development. The subprogram collaborates with state and local organizations and other federal offices and agencies (such as the U.S. Department of Defense, U.S. Department of Transportation, and the U.S. Department of Energy Offices of Science, Fossil Energy, Nuclear Energy, Wind Energy Technologies, Solar Energy Technologies, Geothermal Technologies, and Advanced Manufacturing) to leverage outside activities, coordinate efforts, and build opportunities for new technology applications and deployment.

In Fiscal Year (FY) 2019, Infrastructure and Systems R&D accomplishments included advances in hydrogen materials compatibility R&D, membrane manufacturing, and integrated hydrogen systems. For example, Idaho National Laboratory (INL) began conducting tests with the 25-kW high temperature electrolyzer, which can utilize heat from nuclear power plants to produce hydrogen with up to 30% less electricity than low-temperature electrolysis. Additionally, six of the 29 prototype fuel cell electric buses undergoing performance evaluation by the National Renewable Energy Laboratory (NREL) exceeded the U.S. Department of Energy/U.S. Department of Transportation ultimate target for fuel cell durability of 25,000 hours. The newly established Hydrogen Materials Compatibility (H-Mat) consortium also added more than 10 partners through a competitive funding opportunity announcement (FOA) focused on accelerated test methods and novel, low-cost, durable metals and polymers for use in hydrogen infrastructure.

In support of H2@Scale, the Program hosted a number of workshops with subject matter experts and stakeholders to assess the status, challenges, and opportunities for hydrogen and fuel cells in various applications. In March 2019, the Program hosted the H2@Rail℠ Workshop in collaboration with the U.S. Department of Transportation's Federal Railroad Administration. This workshop aimed to identify research needed to accelerate technology development and industry commercialization regarding the use of hydrogen fuel cell systems in locomotives and rail applications.[2] In September 2019, the Program collaborated with the U.S. Department of Transportation Maritime Administration and the European Commission Fuel Cells and Hydrogen Joint Undertaking to host the H2@Ports Workshop, with the goal of sharing information on the status of hydrogen and fuel cell technologies for maritime applications.[3] Feedback from these workshops is being used to guide Program strategy in FY 2020.

GOAL

The subprogram's goal is to reduce the cost of hydrogen production, storage, use, and transport to enable H2@Scale.

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[1] This subprogram includes Technology Acceleration and naming is consistent with FY 2018–FY 2019 Annual Merit Review and Peer Evaluation Meeting nomenclature for ease of reference. In the FY 2021 Budget Request, Infrastructure R&D will be included in the Hydrogen Fuel R&D subprogram, along with hydrogen production and storage.

[2] Proceedings from the H2@Rail℠ Workshop can be found online at https://www.energy.gov/eere/fuelcells/h2rail-workshop.

[3] Proceedings from the H2@Ports Workshop can be found online at https://www.energy.gov/eere/fuelcells/h2ports-workshop.

OBJECTIVES

Key objectives for Infrastructure and Systems R&D include the following.

- By 2020, establish the potential for magnetocaloric technologies to liquefy hydrogen at twice the energy efficiency of conventional liquefaction plants.
- By 2030, develop manufacturing techniques to reduce the cost of direct hydrogen fuel cell power systems for heavy-duty trucks at high volume (100,000 units/year) to $80/kW (from the 2019 value of $97/kW).
- By 2025, conduct early-stage R&D to enable technologies that reduce the cost of hydrogen delivery and dispensing to $7/kg.

FY 2019 TECHNOLOGY STATUS AND ACCOMPLISHMENTS

In FY 2019, Infrastructure and Systems R&D initiated three first-of-a-kind demonstrations of integrated hydrogen energy systems in Florida, Texas, and the Midwest, in support of H2@Scale. These projects will demonstrate integration of electrolysis with solar power, wind power, and nuclear power; use of landfill gas in hydrogen production; and use of hydrogen in fuel cell backup power at data centers, in nuclear power generation, and in vehicle fueling. These demonstrations will address key challenges with integration and scale-up of hydrogen technologies, such as controls to enable electrolyzers and fuel cells to smooth power supply and/or supply grid services, economic optimization of hydrogen system components, and incorporation of cyber-security considerations.

A key focus of DOE's H2@Scale initiative is advancing technologies that can be used in hybrid energy systems, wherein hydrogen production is integrated with electricity generators and transmission to lower cost and support grid resiliency. Previous technology acceleration R&D established the ability of electrolyzers to meet the performance requirements for responsive load and ancillary services on the grid. In 2019, researchers developed a test facility for high-temperature electrolysis technologies that can monetize process heat from nuclear power plants. Integration of high-temperature electrolysis with nuclear power can increase the capacity factors of nuclear power generators and reduce the electrical energy consumption of electrolysis by up to 25%.[4]

The Program also kicked off six new projects with more than 15 new stakeholders to collaborate with the H-Mat consortium on materials compatibility R&D. These projects are focused on lowering the cost of metals used in hydrogen compressors, nozzles, and storage vessels; increasing the life of hydrogen dispensing hoses; and lowering the cost of research in high-pressure hydrogen. Project teams will leverage key capabilities within H-Mat, including experimentation under high-pressure hydrogen, advanced techniques to visualize material microstructures, and expertise to inform project direction. Projects will also share their data with the H-Mat data portals for public use by the research community as appropriate.

The Program also continued several projects initiated in previous years to enable reductions in the cost of hydrogen production and delivery components. The Fuel Cell Technologies Office's (FCTO's) target for the cost of hydrogen production and delivery is $7/gge by 2025.[5] The targeted cost of hydrogen production is $2/gge,[6] and the target cost of hydrogen delivery and dispensing is $5/gge. FCTO additionally has a target to enable a 40% reduction in the footprint of liquid fueling stations by 2022, relative to the 2016 baseline. Examples of ongoing R&D activities to support these targets include: (1) analysis to identify technologies and station designs that can enable a lower footprint without affecting station risk profile, (2) design of magnetocaloric concepts that can liquefy hydrogen at twice the efficiency of conventional concepts, and (3) development of concepts to mitigate boil-off of liquid hydrogen.

[4] For more information on the electrical energy consumption of low- and high-temperature electrolysis, please see the H2A case studies available here: https://www.nrel.gov/hydrogen/h2a-production-case-studies.html.
[5] https://www.hydrogen.energy.gov/pdfs/15012_hydrogen_early_market_cost_target_2015_update.pdf
[6] https://www.hydrogen.energy.gov/pdfs/12001_h2_pd_cost_apportionment.pdf

In order to achieve FCTO's hydrogen production cost target of $2/gge, advances in electrolyzer manufacturing that enable cost reductions at scale are necessary. In support of this target, FCTO selected one new project in FY 2019 to improve manufacturing techniques for fuel cell electrodes by increasing the speed at which catalyst coated membranes for electrolyzers are manufactured by 100 times. The project also aims to reduce platinum group metal catalyst loading in electrolyzers by 75% and reduce membrane thickness by 50%. The team is led by Nel Hydrogen/Proton OnSite and includes Oak Ridge National Laboratory, the National Renewable Energy Laboratory, General Motors, and Kodak.

Accomplishments

In FY 2019, Program-level accomplishments in Infrastructure and Systems R&D included the following:

- Selected three new projects that would demonstrate the H2@Scale concept at a small scale (e.g., 1 MW) in three regions—Texas, Florida, and the Midwest.
- Coordinated with the Office of Nuclear Energy (NE) to select two projects for nuclear-to-hydrogen demonstrations (one funded by NE and led by First Energy, and one funded by EERE with NE cost share led by Exelon and Nel Hydrogen).
- In collaboration with the Safety, Codes and Standards and Hydrogen Fuel R&D subprograms, added more than 10 partners to the H-Mat national laboratory consortium through a FOA. Key objectives of H-Mat R&D include development of novel polymers to enhance the reliability of seals and dispensing hoses, R&D on damage models to enable an increase in the life of storage vessels, and microstructural engineering to enhance fracture toughness of steels. A key accomplishment of the H-Mat labs in 2019 included the use and validation of advanced visualization techniques (e.g., helium ion microscopy) to visualize changes in polymer microstructure (e.g., separation of plasticizers, void formation) after saturation with hydrogen.
- Completed assessment of liquefaction plant cost and validated based on industry input and real-world installation plans (see Program Record 19001[7]).
- Validated that six of the 29 prototype fuel cell electric buses undergoing performance evaluation by NREL exceeded 25,000 operating hours, with one exceeding 32,000 hours. Twelve have exceeded 20,000 hours to date.
- Awarded three new projects through the Small Business Innovation Research program, focused on:
  - Reducing the cost and increasing the reliability of nozzles for dispensing hydrogen into light-duty fuel cell vehicles
  - Determining the feasibility of using metal-organic frameworks to remove impurities from hydrogen gas streams at the point of use.

Project-Level Accomplishments

Hydrogen Fueling Infrastructure

- A team led by Electricore, Inc. designed and developed an advanced hydrogen mobile fueler capable of fueling approximately 20–40 fuel cell vehicles per day (at up to 70 MPa with -40°C cooling).
- GVD Corporation tested their polytetrafluoroethylene coating on O-rings after hydrogen exposure. Testing under use conditions showed less visible wear and a 40x longer lifetime for coated O-rings relative to uncoated O-rings. GVD made their first commercial sale in January 2019.
- To address the need for hydrogen compressors with lower cost, higher efficiency, and higher reliability, Giner ELX demonstrated an electrochemical hydrogen compressor at an operating hydrogen outlet pressure of 875 bar and varying hydrogen inlet pressures (1–100 bar). In addition,

[7] Current Status of Hydrogen Liquefaction Costs, Program Record 19001, September 2019, https://www.hydrogen.energy.gov/pdfs/19001_hydrogen_liquefaction_costs.pdf

they demonstrated the ability of the electrochemical hydrogen compressor to operate at 276 mV/cell at 1,000 mA/cm^2 and validated scaled-up membrane electrode assembly components (membranes and distributor plates were scaled from 50 cm^2 to 300 cm^2).

Liquid Hydrogen Technologies

- Washington State University, working with Plug Power, validated computational fluid dynamics analysis of three different hydrogen vortex tube designs (air-filled, rifled, and benchtop). For the first time ever, the team subsequently 3D printed a vortex tube with optimized surface features. Information gathered from experimentation on this prototype tube will inform iterations in tube design to enable the use of vortex tubes in increasing liquid hydrogen pump volumetric efficiency through vapor separation and subcooling, reducing liquid hydrogen storage tank boil-off through thermal vapor shielding and increasing isentropic efficiency of supercritical hydrogen expansion for reliquefaction.

Manufacturing R&D

- NREL and the Colorado School of Mines compared the performance of roll-to-roll coated gas-diffusion electrodes and determined that the slot-die coated component performs better than the gravure-coated electrode. Both methods are >200x faster than lab-scale spray coating while maintaining membrane electrode assembly performance.
- 3M identified, developed, and demonstrated advanced pilot-scale fabrication processes capable of producing proton exchange membrane water electrolyzer components (membranes, anode and cathode powder catalysts and electrodes, and catalyst coated membranes) at an overall 4.3x areal rate relative to the pre-project baseline, exceeding the first year project target. The performance of catalyst coated membranes fabricated with the processes exceeded the final project targets, with a total platinum group metal loading of 0.59 mg/cm^2. Lastly, the project anode catalyst/electrode had exceptional durability, with decay rates of <4 µV/h over 1,900 hours at 80°C, 2 A/cm^2 with an electrode Ir loading of just 0.42 mg/cm^2.
- Mainstream Engineering developed a testing apparatus for examining and analyzing membrane sheets that utilizes a linescan camera, programmable linear stage, and industrial controller with custom image processing software. In addition, they demonstrated catalyst loading measurement (via image pixel intensity), real-time defect detection (down to 25 microns), and thickness calculation (17–250 microns) for several industrial membrane samples using the Mantis Eye platform.
- NREL completed a co-funded project with Gore, providing full-length, full-width in-line quality mapping of 14 production and experimental rolls of Gore Select Membrane, using NREL-developed automated feature detection and classification algorithms, for a total scanned length of over 1.6 kilometers. This successful demonstration of in-line, automatic defect detection enables adoption by membrane manufacturers and end users.
- NREL demonstrated in-line membrane thickness mapping on 100+-meter rolls of polymer electrolyte membranes from Gore, Chemours, and 3M, as well as other suppliers, in single- and multi-layer constructions at line speeds of up to 5 feet per minute. The achieved x (cross-web) and y (down-web) resolutions of 0.1 mm and 0.3 mm, respectively, were dependent on line speed and imager capabilities (pixel density, frame rate and field of view). The achieved z (thickness) resolution of 0.2 µm is a small fraction of state-of-the-art fuel cell membrane thickness. Effective z resolution is critical for membrane manufacturers, as even small membrane thickness variations can impact cell performance and lifetime.

Fuel Cell Technology Validation

- Validated two prototype fuel cell hybrid electric parcel delivery vans. A FedEx delivery van was deployed in upstate New York and a UPS delivery van was deployed in California. These first-of-a kind prototype delivery vans were designed to extend the battery-electric vehicle range. The FedEx prototype was deployed on FedEx routes in Albany, New York. It demonstrated a range increase from 60 to 150 miles and logged over 15,000 miles in service. Assembly and validation testing were completed for the UPS prototype delivery van, which enabled it to begin operations on UPS routes in West Sacramento, California.

Systems Analysis

- National laboratory researchers from Argonne National Laboratory, INL, and NREL completed studies for hydrogen supply and demand to support H2@Scale. The studies included demand for transportation, refineries, chemical processing, metals refining, ammonia production, hydrogen use for biofuels and synthetic fuels, direct injection into the nation's natural gas system, and energy storage. Analysis was also completed on hydrogen supply from steam methane reforming and high-temperature electrolysis with nuclear power and renewable power resources. The results are being expanded to incorporate additional hydrogen demands and will ultimately quantify the "maximum market potential" and "economic potential" of H2@Scale.

Hybrid Energy Systems R&D

- INL began conducting tests with the 25-kW high temperature electrolyzer to: (1) demonstrate response rate to support the grid, (2) analyze stack degradation based on real-time measurements of stack performance, and (3) characterize high-temperature electrolyzer performance under dynamic grid conditions. High-temperature electrolyzers have the potential to utilize heat from nuclear power plants to produce hydrogen with up to 30% less electricity than low-temperature electrolysis.
- A team of researchers from NREL, Washington State University, and Pacific Northwest National Laboratory developed a building energy dispatch controller optimization tool that, among other objectives, explores how stationary fuel cells can be used for combined heat and power to meet a building's electrical and thermal loads**.** Initial co-simulation results suggest that cost savings to building operation could be on the order of 5% even in places with high natural gas and low electricity rates. A hardware-in-the-loop experiment is planned for early FY 2020 to add to the insights.
- A team of researchers from Lawrence Berkeley National Laboratory, NREL, and INL developed a hydrogen vehicle-to-grid integrated (H2-VGI) tool that has modeled the interaction of flexible hydrogen generation from electrolysis and the electricity grid. Results showed that flexible hydrogen generation can provide net load ("duck curve") benefits in California for peak shaving, valley filling, and ramp-rate mitigation. In addition, using the electricity grid production cost model (PLEXOS), the research team found that increasing hydrogen production flexibility for 5 million fuel cell electric passenger vehicles and 0.33 million medium- and heavy-duty fuel cell trucks can provide grid benefits for the Western U.S. grid in 2030 (such as lower generation cost, lower renewable electricity curtailment, and lower greenhouse gas emissions).

New Project Selections

In FY 2019, the Program added the following new projects through funding opportunity announcements.

- Six projects will support the H-Mat consortium through materials research to improve the durability and performance of hydrogen fueling components. (Clemson University; Colorado School of Mines; Hy-Performance Materials Testing, LLC; Massachusetts Institute of Technology; The University of Alabama; University of Illinois at Urbana-Champaign)
- Three pilot projects will demonstrate the integration of hydrogen production, storage, distribution, and utilization to support the H2@Scale vision. (Exelon Corporation; Frontier Energy, Inc.; Giner ELX, Inc.)
- Three projects were selected to support high-throughput hydrogen fueling for medium- and heavy-duty transportation through research on compressor, cryopump, nozzle, and related technologies. (Air Products and Chemicals, Inc.; Nel Hydrogen Inc.; Electricore, Inc.)

BUDGET

The FY 2019 budget for Infrastructure and Systems R&D projects totaled about $44 million. The funding breakout is shown in Figure 1 and includes $21 million appropriated for Infrastructure R&D, $21 million for Technology Acceleration R&D, and $2 million for Systems Analysis. This funding included $10 million for integrated hydrogen systems, $4 million for early-stage manufacturing, $11 million for heavy-duty applications, $11 million for light-duty vehicle station component R&D (including materials compatibility), and $6 million for hydrogen liquefaction and carriers. The funded projects support the H2@Scale initiative, which includes new, non-light-duty vehicle sectors and integrating electrolyzers to support the electric grid.

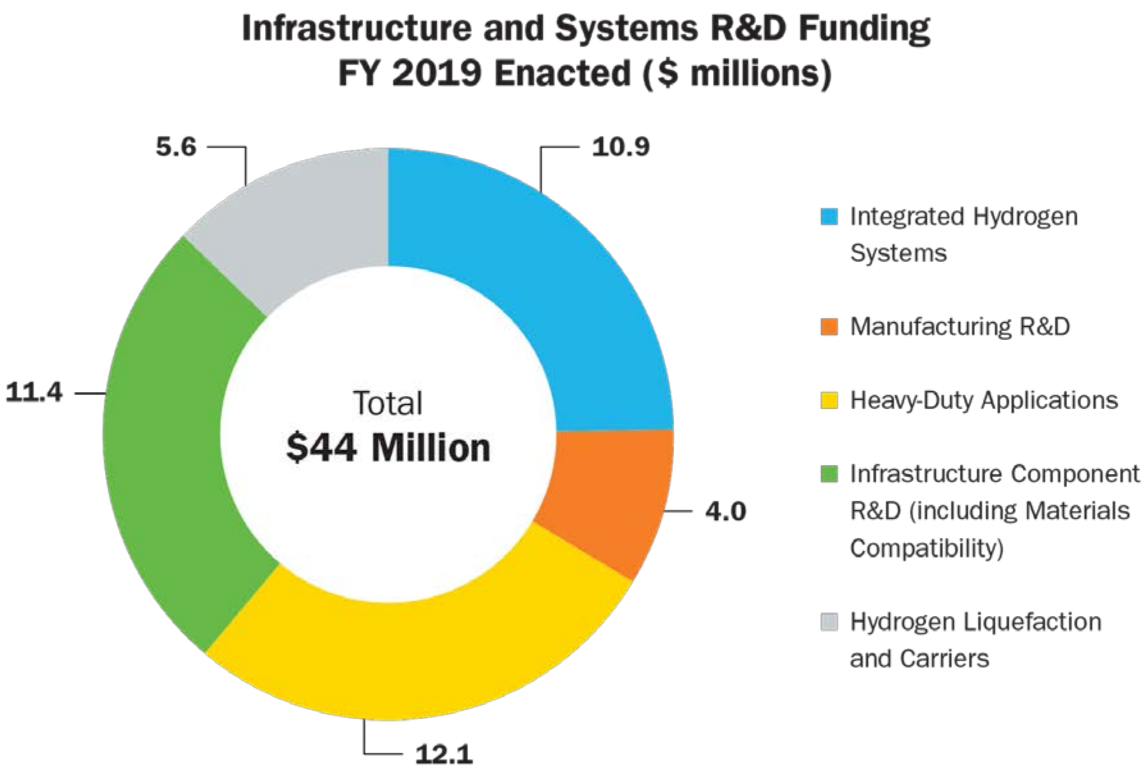

Figure 1. Infrastructure and Systems R&D subprogram FY 2019 enacted budget

UPCOMING ACTIVITIES AND PLANS

The future plans for Infrastructure and Systems R&D, pending funding appropriations, include the following.

- Foster new markets for hydrogen, especially in emerging industrial applications, such as the use of hydrogen in steel manufacturing and iron refining applications.
- Develop first-of-a-kind demonstrations in emerging new markets for hydrogen, aligned with H2@Scale priorities. Efforts will focus on integrated systems that demonstrate hydrogen production, delivery, dispensing, storage, and utilization, tailored to new applications. Two areas of particular interest are hydrogen and fuel cells in the maritime sector and primary and/or backup power at data centers.
- Continue research, development, and demonstration on infrastructure components and system integration, particularly integrating with the grid, and validate technologies under real-world conditions to help guide future R&D.

- Continue to leverage cross-office and cross-agency R&D opportunities and resources, including expanded collaboration with the Office of Nuclear Energy and the Office of Fossil Energy. Examples include co-funded demonstration of hydrogen production at a nuclear plant, aligned with H2@Scale.

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[i] For FY 2019 and through Q1 FY 2020
[ii] As of February 1, 2020