III.0 Hydrogen Delivery Sub-Program Overview

INTRODUCTION

The Hydrogen Delivery sub-program addresses all hydrogen transmission, distribution, and dispensing activities between the point of production and the fuel cell. Research and development (R&D) activities address challenges to the cost and performance of hydrogen infrastructure, including compatibility of commonly used materials with hydrogen, efficiency of hydrogen liquefaction, development of non-mechanical station compressors, lowering the costs of hydrogen storage, and enhancing the durability and accuracy of hydrogen dispensers. Technoeconomic analysis is used by the sub-program to identify drivers of hydrogen cost and barriers to widespread growth, which inform sub-program planning and portfolio development.

GOAL

The goal of this sub-program is to enable R&D advancements that reduce the costs associated with delivering hydrogen to a point at which its use as an energy carrier in fuel cell applications is competitive with alternative transportation and power generation technologies.

OBJECTIVES

The objective of the Hydrogen Delivery sub-program is to conduct R&D that lowers the cost of hydrogen dispensed at the pump to a point at which fuel cell electric vehicles are competitive on a cents-per-mile basis with competing vehicle technologies. Based on current analysis, this translates to a hydrogen cost of <$7 per gallon gasoline equivalent (gge) (produced, delivered, and dispensed, but untaxed) by 2020.[1] In the long term, an ultimate target of <$4/gge (produced, delivered, and dispensed, but untaxed) has been set for mature markets with economies of scale.[2] This cost target has been apportioned to be <$2/gge for production and <$2/gge for delivery and dispensing.[3] The sub-program plans to meet these objectives by developing low-cost, efficient, reliable, and safe technologies to deliver hydrogen from the point of production to the point of use in both stationary fuel cells and fuel cell electric vehicles. Key objectives for specific delivery components include:

- **Station Technologies:**
  - Compression: Enhance the durability of components in conventional compressors, and develop early-stage non-mechanical technologies with potential for high-pressure hydrogen compression.
  - Storage: Develop novel designs that lower the costs of hydrogen storage vessels, guided by materials compatibility R&D.
  - Dispensers: Develop novel materials and metering technologies to improve the cost, reliability, and accuracy of 700 bar dispensers.
- **Materials Compatibility:** Identify microstructures of steel with superior resistance to hydrogen embrittlement, and develop a constitutive model of hydrogen-assisted fatigue.
- **Liquid Hydrogen Technology:** Investigate novel approaches to hydrogen liquefaction (e.g., use of superconducting magnets or vortex tubes) with potential to achieve capital and operating costs substantially lower than those of conventional liquefiers.
- **Analysis:** Conduct comprehensive analyses on near- and long-term hydrogen delivery options to identify the advantages of each and areas for potential improvement.

---

[1] *Early Market Hydrogen Cost Target Calculation—2015 Update*, Program Record (Fuel Cell Technologies Office) 15012, U.S. Department of Energy, 2015. https://www.hydrogen.energy.gov/pdfs/15012_hydrogen_early_market_cost_target_2015_update.pdf

[2] *Hydrogen Threshold Cost Calculation*, Program Record (Office of Fuel Cell Technologies) 11007, U.S. Department of Energy, 2011. https://www.hydrogen.energy.gov/pdfs/11007_h2_threshold_costs.pdf

[3] *H_2 Production and Delivery Cost Apportionment,* Program Record (Hydrogen and Fuel Cells Program) 12001, U.S. Department of Energy, 2012. https://www.hydrogen.energy.gov/pdfs/12001_h2_pd_cost_apportionment.pdf

FISCAL YEAR (FY) 2017 TECHNOLOGY STATUS AND ACCOMPLISHMENTS

In FY 2017, the Hydrogen Delivery sub-program kicked off seven new projects, participated in one workshop, and saw significant progress in R&D activities of existing projects.

Sub-Program Level Accomplishments

In FY 2017, significant progress was made by the Hydrogen Delivery sub-program on several important fronts. Several highlights include:

- Argonne National Laboratory was issued a patent for the tube trailer consolidation strategy[4] developed in 2013. Tube trailer consolidation can lower the capital cost of compression at a fueling station and thereby lower overall station cost by 40%. The strategy involves use of a fueling station's compressor to pressurize the hydrogen in the tube trailer during off-peak hours of a day. As a result, the station has high-pressure hydrogen available during peak hours and is able to achieve higher flow rates than otherwise possible. In this way, a station can satisfy its daily demand with a compressor that costs 60% less than under normal operation.[5] The strategy is being evaluated experimentally at the National Renewable Energy Laboratory (NREL) through the Hydrogen Fueling Infrastructure Research and Station Technology (H2FIRST) project and is also being demonstrated by FirstElement Fuel at a retail station through a Technology Commercialization Fund award.
- WireTough Cylinders developed a design for an 875 bar hydrogen storage vessel that is expected to cost >50% less than those currently on the market. The design is based on wrapping autofrettaged liners with high-strength steel wire, and its cost projections have been independently verified.
- Used materials R&D funded by the U.S. Department of Energy and the U.S. Department of Transportation in the modification of the ASME B31.12 Code for Hydrogen Piping and Pipelines. Evaluations of the performance of high-strength steel and fiber-reinforced polymer in high-pressure hydrogen service over the past decade have led to Code modifications that 1) allow for the use of fiber-reinforced polymer in 170 bar hydrogen service and 2) remove "thickness penalties" on X70 steel used in 100 bar hydrogen service. Each of these modifications can independently lower the installation costs (material and labor) of hydrogen pipelines by 25%.[6]
- Announced four new Small Business Innovation Research (SBIR) awards in the areas of metal hydride materials discovery, magnetocaloric materials development, metal-free hydrogen dispensing hoses, and evaluation of coatings for compressor seals.

Project Level Accomplishments

During FY 2017, progress was made by existing projects in several key areas, including:

Station Technologies

Sub-program efforts on station technologies improve the reliability and reduce the cost of compression, on-site storage, and dispensers.

- In FY 2017, four projects were kicked off to advance non-mechanical concepts for high-pressure hydrogen compression. These projects were all in the areas of electrochemical and metal hydride compression. Electrochemical hydrogen compression involves the use of electrochemical cells to pressurize hydrogen. A catalyst layer on the cell membrane splits hydrogen molecules into protons and electrons on one side of the cell. A voltage is applied to cell electrodes such that the electrons travel through an external circuit toward the other side of the cell (i.e., the cathode side). The resulting charge at the cathode drives diffusion of protons through the cell membrane to the cathode side as well. As a result, high-pressure hydrogen builds up on the cathode. Metal hydride compression, on the other hand, involves use of materials that reversibly absorb and desorb hydrogen at specific temperatures. The supply and removal of heat can therefore be used with metal hydride materials to enable the uptake and/or release of hydrogen at specific pressures. FY 2017 R&D accomplishments in these areas include:

[4] Elgowainy, A. (2017). *U.S. Patent No. 9,739,418*. Washington, DC: U.S. Patent and Trademark Office.
[5] http://www.sciencedirect.com/science/article/pii/S036031991402833X
[6] Cost assessment for fiber-reinforced polymer has been based on consultation with members of industry. Cost assessment for steel is published in: Fekete, J., Sowards, J.W., and Amaro, R.L. "Economic impact of applying high strength steels in hydrogen gas pipelines." International Journal of Hydrogen Energy (2015). < http://www.sciencedirect.com/science/article/pii/S036031991501575X?via%3Dihub >

- Giner is enhancing the durability and current densities of membranes that may be viable in electrochemical hydrogen compression. The project's goal is to compress 0.5 kg H_2/h in an electrochemical cell at 875 bar. In 2017, Giner achieved its target current density for an electrochemical cell (~900 mA/cm^2 at a cell voltage of 0.25 V and a hydrogen pressure of 350 bar). Optimization of the chemical compositions of cell membranes has been implemented to effectively manage water in the cell and therein prevent "flooding" and allow for high rates of hydrogen transport.
- Researchers at Sandia National Laboratories are identifying metal hydrides and modeling compressor designs for an approach to achieve metal hydride compression with an energy efficiency of <4.0 kWh/kg. The aim is to produce a two-stage system of metal hydride beds capable of compressing hydrogen from 100 bar to 875 bar on the laboratory scale, along with comprehensive cost analysis for full scale (100 kg H_2/h). Metal hydride candidates have already been identified for each compressor stage based on extensive literature research, and their physical properties have been characterized in a custom Sieverts cycling apparatus assembled specifically for compression testing.
- Greenway Energy is combining these two novel technologies, electrochemical hydrogen compression and metal hydride compression, to produce a hybrid system for hydrogen compression. The project will result in the design, fabrication, and testing of their concept at 1–5 kg/day. For the electrochemical hydrogen compression, a polybenzimidazole membrane has been experimentally shown to outperform Nafion at high temperatures and pressures. A thermodynamic model of the complete system has been completed; the metal hydride compression is driven by waste heat produced by the electrochemical hydrogen compression.
- Greenway Energy has been awarded an SBIR grant for discovery of metal hydride materials to be used in high-pressure hydrogen compression. The project team has defined key material properties that metal hydrides must exhibit for use in high-pressure compression and identified a high-throughput approach to material characterization. The characterization approach involves synthesis of a cantilever beam, upon which metal hydrides will be deposited. Motion of the beam will measure hydrogenation/dehydrogenation rates. In parallel, the team has begun development of a computational model to predict enthalpy and entropy properties of metal hydride compositions. The model is being calibrated with data in the public domain (e.g., published in the Hydrogen Storage Materials Database).

- NREL improved the reliability of hydrogen dispensers through evaluations of the impact that cycling at 875 bar and -40°C has on hose material degradation, hose composition, and overall dispenser performance. The relationship between the rate of hydrogen permeation through the hose and hose temperature was assessed, as polymer performance may change near the glass transition temperature (-50°C). With the remaining funding, dynamic mechanical analysis, scanning electron microscopy, and chemical composition testing will be performed to compare the composition and morphology of the hose pre- and post-cycling.
- Argonne National Laboratory performed technoeconomic analysis to assess cost drivers associated with filling medium- and heavy-duty fuel cell vehicle systems. The impacts of various station configurations (e.g., multiple dispensers vs. one dispenser, supply by liquid tankers vs. tube trailers) and fill parameters (e.g., flow rate) on station cost were evaluated.
- Through H2FIRST, Sandia National Laboratories and NREL published a report detailing the designs and costs of several common types of hydrogen fueling stations, including those with on-site reforming of natural gas or electrolysis and those that are delivered pre-packaged. The report is now publicly available here: https://energy.gov/sites/prod/files/2017/03/f34/fcto-h2first-reference-station-phase2-2017.pdf.
- Ivys Energy Solutions initiated a project to develop a durable, high-accuracy (at least 2% accuracy) dispenser. To date, the team has quantified the impacts that key variables (e.g., weather, transients during fueling, manufacturing tolerances) can have on meter accuracy. They have also researched dedicated short-range communications hardware for integration into their dispenser, to enable wireless communication between the dispenser and the vehicle.
- NanoSonic made progress in the development of a new metal-free hydrogen dispensing hose, expected to cost 2x less than the current state of the art and weigh 25% less. Over the past year, use of a novel ceramer has nearly doubled the burst strength of the hose to 31,000 psi. Future work will focus on development of hose fittings to increase durability, as well as iterations on fiber reinforcement.
- GVD Corporation reduced erosion of seals used in hydrogen compressors by over 70% using an innovative coating process developed at the Massachusetts Institute of Technology. Over the past year, the deposition process

of these coatings has been optimized, and testing of coating performance was conducted at PowerTech Labs. In the next year, the coatings will be tested for hydrogen permeation on compressors at NREL and will be optimized for use in dispensers as well.

Materials Compatibility

Structural steels are widely used in hydrogen infrastructure, such as in pipelines, compressors, and pressure vessels. A microstructure-based understanding of hydrogen-induced damage (i.e., hydrogen embrittlement) in steels can enhance the reliability and lower the costs of components by enabling the use of alloys that are currently assumed to be unsuitable. The Delivery sub-program's current project in this area is identifying microstructures with enhanced resilience to hydrogen effects, with the goals of (1) developing a novel steel alloy and (2) informing the development of a constitutive model of hydrogen embrittlement.

- The project team has completed triplicate measurements of fatigue crack growth in specimens of X100 base metal and welds and evaluated the impact that "residual stresses" have on specimens' resistance to fatigue; accounting for residual stresses allows for the impacts of microstructure alone to be more accurately estimated. Additionally, the team has generated samples of steel with gradient microstructures (i.e., Gleeble specimens) that will be tested in FY 2018. These specimens will allow for comparisons to be made of the performance of various microstructures in hydrogen. Finally, the data being generated experimentally is being used to calibrate a constitutive model of hydrogen embrittlement developed at Colorado School of Mines in collaboration with the U.S. Department of Transportation and the National Institute of Standards and Technology.

Liquid Hydrogen Technologies

Liquefaction represents more than 50% of the cost of hydrogen delivered to vehicles via liquid fueling stations. DOE is funding research to lower the costs of liquefaction, as well as the costs of utilizing liquid hydrogen at fueling stations.

- Pacific Northwest National Laboratory is developing a concept for hydrogen liquefaction using superconducting magnets and magnetocaloric materials, with the goal of liquefying hydrogen at twice the efficiency of conventional cycles. Magnetocaloric materials cool down in the presence of a magnetic field. In FY 2016, Pacific Northwest National Laboratory set a world record by achieving a 100-K temperature span with these materials and a 3.3-Tesla superconducting magnet. In FY 2017, researchers identified 14 alloys that can be layered and achieve the full temperature span targeted (280 K – 20 K) for hydrogen liquefaction, and they synthesized the first eight using an innovative approach known as rotating disk atomization. Models of regenerator performance were validated with experimentation on individual layers, and approaches to managing heat transfer between layers are being developed.
- At Lawrence Livermore National Laboratory, thermodynamic models of liquid hydrogen behavior (e.g., heat transfer and resulting evaporation) are being used to simulate boil-off losses from hydrogen infrastructure, such as dewars at fueling stations and/or liquid tankers. These models are meant to inform strategies to mitigate boil-off. They are additionally being used in conjunction with data on vehicle driving patterns to assess the economic viability of cryo-compressed hydrogen use in vehicles.

Workshops

The *Fifth International Workshop on Hydrogen Infrastructure and Transportation*, organized by the National Organisation Hydrogen and Fuel Cell Technology (NOW) of Germany, the New Energy and Industrial Technology Development Organization (NEDO) of Japan, the European Commission's Joint Research Center, and DOE, was held in May of 2017 in Berlin, Germany. This workshop included members of industry, academia, and government—Japan, Germany, the European Union, China, Scandinavian countries, and the United States. Key takeaways from the workshop are summarized in Table 1 below.

TABLE 1. Key Issues Discussed at the 5th International Infrastructure Workshop

Fueling	Germany, Japan, and the United States all have devices in place to collect data for validation of stations against refueling requirements. Inconsistences in station design can challenge operation of these devices. In Germany, the world's first fuel cell powered train is also being developed and will require new fueling protocols.
Hydrogen Quality	Members of government and industry in Germany, Japan, and the United States are working toward the development of inline contaminant detectors for fueling stations. Efforts are focused on identifying priority contaminants (those with greatest likelihood of occurrence, or likely to cause the greatest damage to a fuel cell).
Metering	Germany, Japan, and the United States are all currently permitting hydrogen sales at lower accuracies than the target of 2%. In the meantime, each country has ongoing R&D to develop new meters, develop meter test devices, and identify the causes of meter inaccuracies. While the accuracy of 2% is often achieved, outliers (e.g., due to vibrations from traffic or weather) can reduce the accuracy to up to 10%.
Hardware	While station availability has increased, compressors and chillers remain the primary causes of station down-time. An additional concern internationally is the ergonomics of dispensers.
Hydrogen Logistics	Innovative mechanisms of hydrogen delivery and/or uses of hydrogen fuel cells are being explored internationally. Liquid chemical carriers are being developed in Japan to allow for hydrogen imports. In the United States, non-mechanical approaches to hydrogen liquefaction are being explored to lower the costs of liquid hydrogen delivery.

Publications

NREL published the "Comparison of conventional vs. modular hydrogen refueling stations, and on-site production vs. delivery" report.[7] This report details standard designs and expected costs of hydrogen fueling stations with hydrogen production on site (in the form of steam methane reforming or electrolysis), as well as pre-assembled (i.e., modular) stations.

FY 2017 Funding

In FY 2017, DOE announced four SBIR awards and one Technology Commercialization Fund award:

- Greenway Energy was awarded an SBIR Phase I award to develop an approach to metal hydride materials discovery. It has begun machine learning, as well as high-throughput computation toward this project, as detailed above.
- General Engineering and Research LLC was awarded an SBIR Phase II award to optimize its approach to synthesizing low-cost magnetocaloric materials of interest to hydrogen liquefaction.
- GVD Corp. was awarded an SBIR Phase IIA award to modify the deposition process for its coatings, to allow for use in hydrogen dispensers. These coatings will also be tested in compressors at NREL.
- NanoSonic, Inc. was awarded an SBIR Phase IIB award to develop fittings for hydrogen dispensing hoses and optimize the design of the dispensing hose they developed in Phase II.
- Argonne National Laboratory was given a Technology Commercialization Fund award to demonstrate the tube trailer consolidation strategy at a retail hydrogen fueling station. The strategy can lower the costs of a hydrogen compressor at a fueling station by 60% and is described above under "Project Level Accomplishments."

Additional FY 2017 funding will be directed toward awards made under the H2@Scale Cooperative Research and Development Agreements Call.

BUDGET

The FY 2017 appropriation for Hydrogen Production and Delivery projects totaled $25.4 million. With the emphasis on supporting H2@Scale and on advanced technologies for fueling station, hydrogen liquefaction, and large-scale delivery options, the apportionment of this funding in the Hydrogen Delivery and Dispensing portfolio was approximately $9.3 million. The estimated budget breakdown for Hydrogen Delivery and Dispensing in FY 2017 is shown in Figure 1.

[7] https://energy.gov/sites/prod/files/2017/03/f34/fcto-h2first-reference-station-phase2-2017.pdf

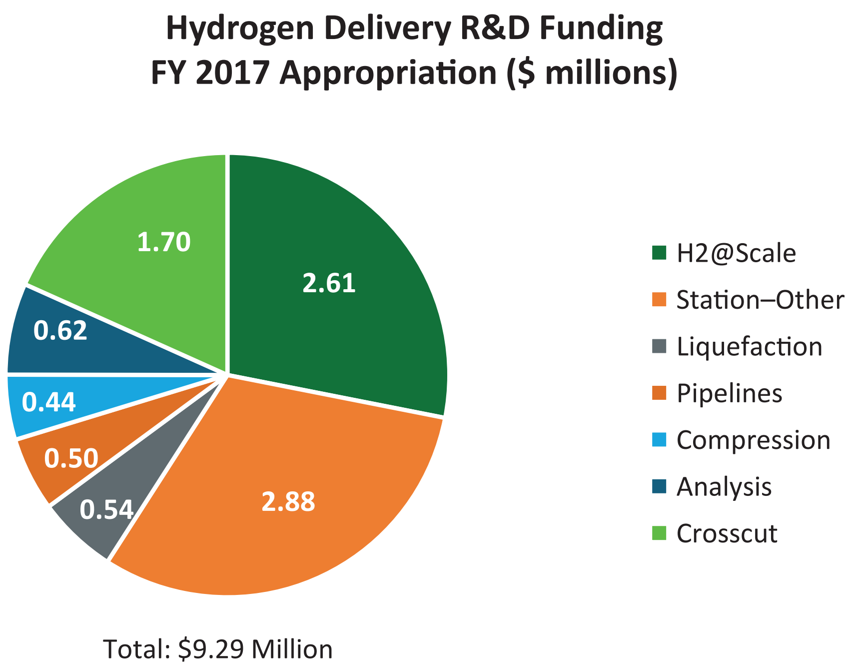

FIGURE 1. FY 2017 Appropriations

UPCOMING ACTIVITIES AND PLANS

In FY 2018, the Hydrogen Delivery sub-program will focus on several key efforts, including:

- Advancing non-mechanical magnetocaloric liquefaction concepts to enable hydrogen liquefaction with 2X efficiency, in support of H2@Scale.
- Early-stage materials development to enhance service lives and lower costs of fueling station components.
- Exploratory R&D to assess the potential of chemical carriers for high-volume hydrogen storage and delivery.

Future activities are subject to appropriations.

Neha Rustagi
Hydrogen Production and Delivery Technology 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) 586-8424
Email: Neha.Rustagi@ee.doe.gov