III.0 Hydrogen Delivery Sub-Program Overview

INTRODUCTION

The Hydrogen Delivery sub-program addresses all hydrogen transmission and distribution activities from the point of production to the point of dispensing. Research and development activities address challenges to the widespread commercialization of hydrogen technologies in the near-term through development of tube trailer and liquid tanker technologies as well as forecourt compressors, dispensers, and bulk storage; and in the mid- to long-term through development of pipeline and advanced delivery technologies. Technoeconomic analysis is used by the sub-program to identify cost, performance, and market barriers to commercial deployment of hydrogen technologies, and to inform sub-program planning and portfolio development.

GOAL

The goal of this sub-program is to 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 reduce the cost of hydrogen dispensed at the pump to a cost that is competitive on a cents-per-mile basis with competing vehicle technologies. Based on current analysis, this translates to a hydrogen threshold cost of less than $4 per gallon gasoline equivalent (gge) (produced, delivered, and dispensed, but untaxed) by 2020,[1] apportioned to less than $2/gge for delivery and dispensing.[2] The sub-program plans to meet these objectives by developing low-cost, efficient, 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. This objective applies to all of the possible delivery pathways. Key objectives for specific delivery components include:

- **Tube Trailers:** Reduce the cost of compressed gas delivery via tube trailer by increasing vessel pressure to 520 bar and lowering trailer capital cost on a per-kilogram-of-hydrogen-transported basis to less than $575/kg by 2020.
- **Pipeline Technology:** Advance the development and acceptance of alternative composite pipe materials that can reduce installed pipeline costs through inclusion in the American Society of Mechanical Engineers (ASME) B31.12 code by 2015.
- **Liquid Delivery:** Reduce the capital and energy use of small-scale hydrogen liquefiers to less than $42M and less than 8 kWh/kg by 2015.
- **Forecourt Technologies:** Reduce the cost and improve the reliability of compression, storage and dispensing technologies to achieve a station cost contribution of less than $1.60/gge by 2015.

FISCAL YEAR (FY) 2014 TECHNOLOGY STATUS AND ACCOMPLISHMENTS

In FY 2014, the Hydrogen Delivery sub-program made five new awards, held two workshops, and saw significant progress in RD&D activities of existing projects. Significant accomplishments included:

- The release of Hydrogen and Fuel Cells Program Record #13013 documenting the changes in costs of hydrogen delivery technologies from 2005 to 2013, and projecting future costs.[3]
- Five new awards, three selected from the FY 2014 Hydrogen Delivery Funding Opportunity Announcement (FOA) and two from Small Business Innovation Research (SBIR) projects on compression, storage, and dispensing technologies.

[1] *Hydrogen Threshold Cost Calculation*, Program Record (Office of Fuel Cell Technologies) 11007, US Department of Energy, 2012, http://www.hydrogen.energy.gov/pdfs/11007_h2_threshold_costs.pdf

[2] *Hydrogen Production and Delivery Cost Apportionment*, Program Record (Office of Fuel Cell Technologies) 12001, US Department of Energy, 2012; http://hydrogen.energy.gov/pdfs/12001_h2_pd_cost_apportionment.pdf

[3] http://energy.gov/eere/fuelcells/downloads/fuel-cell-technologies-office-multi-year-research-development-and-14

- Two workshops to foster collaboration between industry, academia, and the international community in identifying the current challenges and RD&D needs of forecourt technologies to reduce costs and improve system reliability.
- The *Hydrogen Station Compression, Storage, and Dispensing Technical Status and Costs* report was published by the National Renewable Energy Laboratory (NREL) in 2014. This report is an independent panel review of the current status and RD&D needs of hydrogen delivery technologies.
- The Hydrogen Fueling Infrastructure Research and Station Technology (H2FIRST) project was initiated in April of 2014 to conduct RD&D on the development of a hydrogen infrastructure. The project is a collaboration between Sandia National Laboratories (SNL) and NREL and was developed to support H2USA.

Workshops

The first delivery workshop was the *Hydrogen Transmission and Distribution Workshop*, held in February of 2014. This workshop identified technical challenges in the transmission and distribution of hydrogen from the point of production to the point of use in consumer vehicles at a cost of <$3/gge by 2015 and <$2/gge by 2020.[4] Participants included experts from the natural gas industry, national laboratories, academia, and the National Institute of Standards and Technology. The workshop was divided into discussions on pipelines, including pipeline materials and compression, and over-road distribution, including gaseous, liquid, and hybrid distribution. The key challenges and RD&D requirements identified within these areas are summarized in Tables 1 and 2.

TABLE 1. Key Pipeline Areas Discussed

	Challenges	RD&D Needs
Pipeline Compression	Compressor reliability and maintenance requirements	Development of novel compressor systems. *Long-term*: Development of compressors with line packing capability.
	Optimization of performance and cost of high-pressure compressors	High-volume manufacturing of miniaturized parts. Integration of purification, cooling, and compression systems.
	Optimization of hydrogen transmission and distribution routes	Techno-economic models to optimize key variables, e.g. storage capacity and pressure. *Long-term:* A model addressing the interface between hydrogen pipelines and the electric grid.
	Evaluation and comparison of existing technologies	Facilities that provide third-party validation of compressor performance and define procedures to assess key metrics.
Pipeline Materials	Physical understanding of hydrogen-induced damage mechanisms	Research on the performance of high-strength steels and welds in hydrogen service and identification of the material properties that affect hydrogen embrittlement. *Long-term:* Development of a physics-based predictive fatigue crack growth model informed by testing.
	Joining technologies	Evaluation of existing non-metallic materials and development of new cost effective and reliable joining technologies for fiber-reinforced polymer (FRP) pipelines.
	Capital cost of pipeline installation	Demonstration of FRP in hydrogen transport at scale in a variety of soil types. *Long-term:* Development of a machine that can manufacture FRP in situ.
	Codes and standards adoption	Burst and fatigue testing of FRP in hydrogen, and measurement of permeation rates to develop the technical basis for factors of safety. Development of efficient inspection and monitoring techniques.

[4] The "Hydrogen Transmission and Distribution Workshop" proceedings are available here: http://energy.gov/sites/prod/files/2014/07/f17/fcto_2014_h2_trans_dist_wkshp_summary_report.pdf

TABLE 2. Key Over-Road Distribution Areas Discussed

	Challenges	RD&D Needs
Distribution via Gaseous Tube Trailers	Understanding of degradation mechanisms	Test procedures and acceptance criteria for polymers in hydrogen. Research on the degradation of polymers and composite vessels under high-pressure hydrogen cycles.
	High capital and operating costs	Discovery and qualification of low-cost, lightweight structural alloys for use in high-pressure trailers. Techno-economic analysis of supply chain models.
	Design limitations of tube trailers	Development of gaseous sorbent materials for low-pressure delivery. Design optimization of tube trailers.
Liquid and Hybrid Distribution	Energy intensity of liquefaction process	Efficiency improvements to pre-cooling, compression, cryo-cooling, expansion, and power recovery systems. Modular high-efficiency liquefaction technologies.
	Length of time required for standards and regulations development	Risk analysis of liquid hydrogen releases. Develop a comprehensive source for information on regulations, codes and standards.
	Increase truck payload	Carrier material development. Low-cost, lightweight structural alloys for low-temperature operation.

The *Second International Workshop on Hydrogen Infrastructure and Transportation,* organized by Germany's NOW (National Organisation Hydrogen and Fuel Cell Technology), Japan's NEDO (New Energy and Industrial Technology Development Organization), and DOE was held in June of 2014, hosted by Toyota at the Toyota Motor Sales Corporate Accessory Center in Torrance, California. This workshop included members of industry and government from Japan, Germany, the European Union, Scandinavia, and the United States. Participants identified the major challenges and RD&D needs of hydrogen fueling protocols, metering, hydrogen fuel quality, and forecourt hardware. The highest priority issues in each of these areas are summarized in Table 3. Additional detail will be available in the workshop proceedings when they are published later in calendar year 2014.

TABLE 3. Issues in International Hydrogen Infrastructure

Topic Area	Highest Priority Issue
Fueling	Development of procedures and hardware to enable certification of stations to SAE International technical specification J2601.
Metering	Agreement between metering accuracy requirements established by the National Institute of Standards and Technology and the International Organization of Legal Metrology, and communication of these requirements to industry.
Hydrogen fuel quality	Development of a low-cost method and hardware to continuously monitor hydrogen inline.
Forecourt hardware	Improve the reliability, durability, and cost of hydrogen compression.

Publications

In FY 2014, the Hydrogen Delivery sub-program released Hydrogen and Fuel Cells Program Record #13013 to document the changes in costs of hydrogen delivery technologies from 2005 to 2013, and to project future costs. The 2013 hydrogen delivery cost at 700 bar is between \$3.23/gge and \$4.84/gge (Figure 1), depending on the delivery pathway. To meet the 2020 target of <\$2/gge, additional RD&D is needed across all aspects of delivery, as is discussed in the *Hydrogen Station Compression, Storage, and Dispensing Technical Status and Costs* independent panel report.

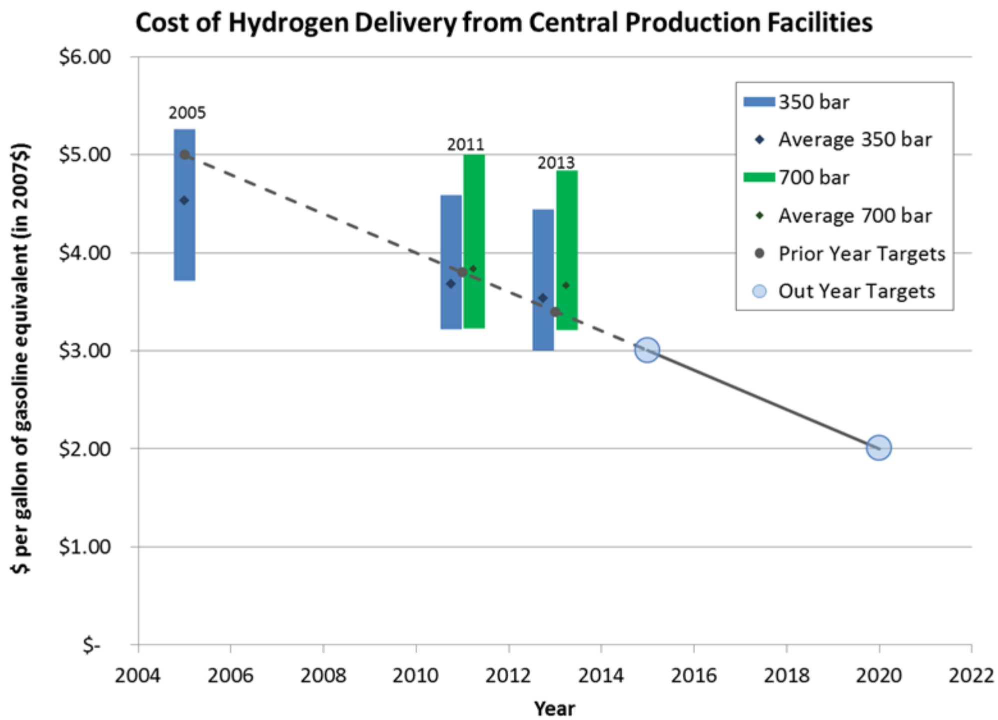


FIGURE 1. Cost of Hydrogen Delivery from Central Production Facilities. The cost statuses and targets of hydrogen delivery (transmission and distribution) have steadily declined since 2005. The ranges shown in this graph are based on simulations of three 350-bar scenarios: (1) transmission and distribution via pipelines, (2) transmission via pipelines and distribution via tube trailers, and (3) transmission and distribution via tube trailers; and five 700-bar scenarios: (1) transmission and distribution via pipelines, (2) transmission via pipelines and distribution via tube trailers, (3) transmission and distribution via tube trailers, (4) transmission via pipelines and distribution via liquid tankers, and (5) transmission and distribution via liquid tankers. Cost statuses for prior years were based on the technology readiness levels during those years. Cost projections are based on DOE targets and feasibility assumptions from technical experts.

For the conditions studied in the record, the lowest-cost transport method was identified as the use of tube trailers for both transmission and distribution. Tube trailers were also the lowest-cost delivery method identified in the *Hydrogen Station Compression, Storage, and Dispensing Technical Status and Costs* independent panel report. The record assumes hydrogen production takes place 100 km from the edge of a U.S. city of average size (Indianapolis was the basis for the analysis), with a market penetration of 10-15%, and a station dispensing rate of 750-1,000 kg/day.

Funding Opportunity Announcements

The Hydrogen Delivery Technologies FOA (DE-FOA-0000821) was announced in 2014, and three award selections are currently being negotiated. The FOA sought research on hydrogen compression, dispensing, and storage technologies that could help bring the cost of hydrogen delivery to less than $2/gge. The awards being made are:

- Southwest Research Institute® ($1.8M), Rockville, MD: *Linear Motor Reciprocating Compressor*. This project involves the design and development of a linear motor reciprocating compressor over the course of three years. In a linear motor reciprocating compressor, the piston contains a permanent magnet that interacts with electromagnetic windings in the cylinder to thrust the piston, and thereby compress the gas. The compressor design is advantageous because it has few moving parts and can be easily modularized.
- Wiretough Cylinders ($2.0M), Bristol, VA: *Low Cost Hydrogen Storage at 875 bar by using Steel Liner and Steel Wire Wrap*. This project involves the development and testing of Type II vessels that can store hydrogen at 875 bar at a cost of $650/kg of hydrogen, exceeding the DOE target of $1,000/kg by 2020.
- Oak Ridge National Laboratory (ORNL) ($2.0M), Oak Ridge, TN: *Low-Cost Steel Concrete Composite Vessel for Forecourt Hydrogen Storage at 875 Bar or Greater*. This project involves the design and development of a prototype of a steel concrete composite vessel that can store hydrogen at 875 bar at $800/kg, exceeding the DOE target of $1,000/kg by 2020.

Tube Trailers and Bulk Storage

Significant cost reduction at the forecourt can be achieved through the use of high-pressure tube trailers and low-cost on-site storage. Higher pressure tube trailers at the forecourt can move the gaseous compression upstream to the tube trailer terminals where economies of scale can reduce the cost of the compression. This year the following two projects have contributed to the cost reduction of the gaseous hydrogen delivery pathway.

- The development of the TITAN™V XL40 trailer configuration for hydrogen delivery was initiated. With a storage capacity of 890 kg of hydrogen and a 90% hauling efficiency, this configuration will increase delivery capacity by 11% over that of the TITAN™V Magnum. The first deployments of TITAN™V Magnum trailers were made in 2013 for compressed natural gas applications. (Hexagon Lincoln)
- A detailed cost analysis of steel/concrete composite vessels that demonstrates the technology's potential to exceed the DOE's 2015 storage cost target of $1,200/kg was completed. (ORNL)

Pipeline Technologies

Pipelines are an attractive delivery pathway for large market scenarios. Advances in both pipeline compression and FRP pipelines continue to improve the economics of the scenario, while work on hydrogen embrittlement of steel continues to improve our understanding of the performance of traditional pipeline materials in use in a hydrogen pipeline transmission and distribution network.

- The inclusion of FRP pipeline with a 50-year design life in the ASME B31.12 code was pursued, and it is expected to be complete by 2015. Fatigue testing has been underway since 2012 at a range of pressures and ratios to support codification efforts. The current data supports an increase in design life from 20 years to 50 years for FRP through a 5% decrease in fiber stress and a limit on fatigue life of 33,100 cycles at an R ratio of 0.5. Experimentation shows that the fatigue life of FRP is highly sensitive to R ratio. (Savannah River National Laboratory, SRNL)
- Triplicate measurements of fatigue crack growth in the base metal, fusion zone, and heat-affected zones of X65 pipeline steel in 21 MPa of hydrogen were collected. The data demonstrate that, at high values of ΔK, crack growth rates are very similar in all three zones. The data collected to date can also be used to determine inspection frequencies for pipelines based on their thicknesses. Experimentation has also been conducted to assess the effect of microstructure on crack growth rate. Crack growth was seen to be slower in banded pearlite microstructures. Further investigation is underway. (Sandia National Laboratories)
- Testing of a single-stage oil-free centrifugal hydrogen compressor in helium was completed in accordance with Industry Standard ASME PTC-10. Vibration of the compressor was very low, reaching a maximum of only 20% of the bearing clearance. The adiabatic efficiency, power requirements, and head of the compressor were additionally strongly correlated with theoretically determined values. Furthermore, the uninstalled capital cost of the compressor was reduced to ~$2M from $2.7M based on a 3,000 kWh motor rating. (Mohawk Innovative Technologies)

Forecourt Technologies

Forecourt technologies, in particular compression and onsite storage, are a key area of focus for the sub-program. Efforts in this area aim to improve the reliability and reduce the cost of the technologies.

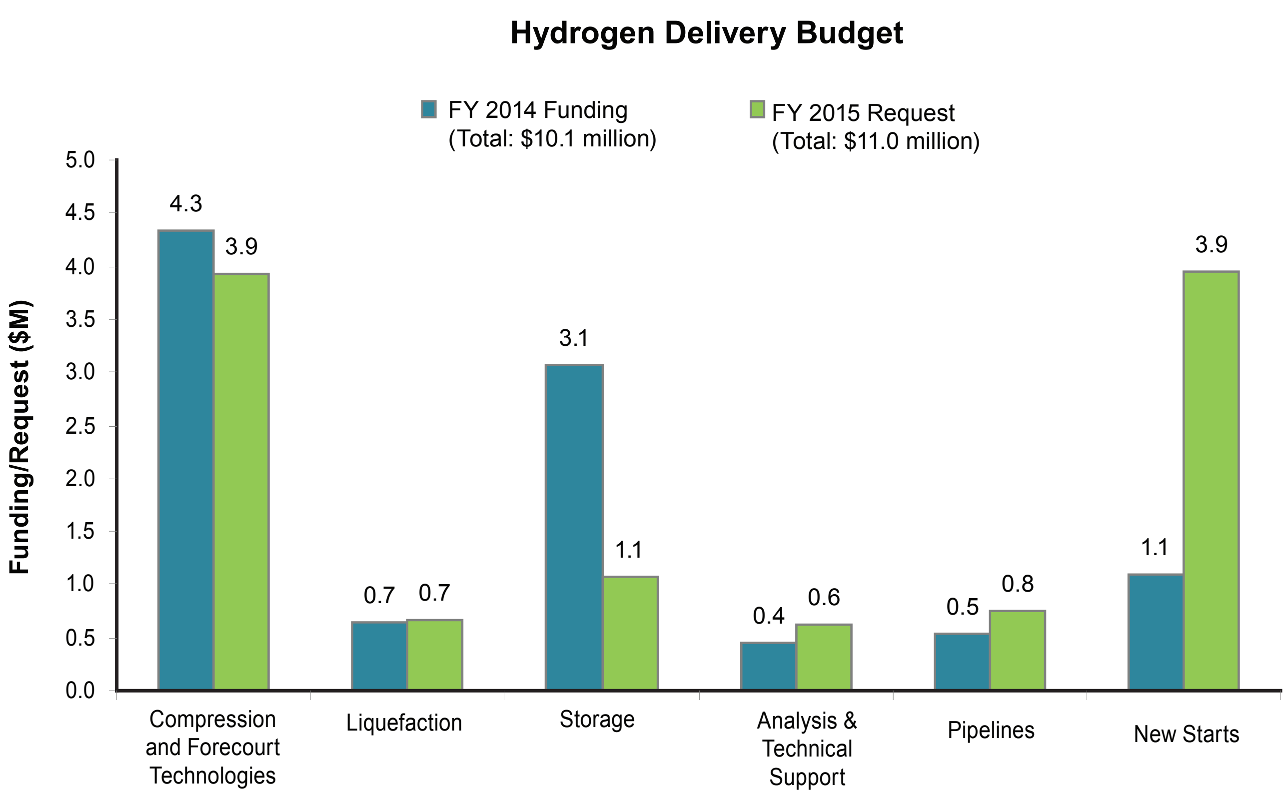
- An 8-cell, 185-cm^2 electrochemical hydrogen compressor stack at a capacity of 2 lb/day with an outlet pressure of 3,000 psi for over 3,800 hours was demonstrated. The 185-cm^2 cell was also validated at over 8,500 hours of operation at current densities greater than or equal to 750 mA/$cm.^2$ The compressor cell design was additionally improved to enable a capital cost reduction of 60% in comparison to the original 2010 design. Design improvements included higher current densities, greater cell active area, increase in stack size, reduction in the number of cell parts, reduction in the cost of cell and stack materials, and reduction in the cost of fabrication. (Fuel Cell Energy)
- A 700-bar refueling hose was tested under simulated mature market conditions to determine the baseline reliability and failure mechanisms from which the technology can be improved. Burst testing has been completed, and the hose material properties have been assessed via spectroscopy, microscopy, calorimetry, and thermal analysis. The hose was found to have a burst pressure of 58,800 psig, more than 105% of its specification. (NREL)
- A fueling strategy to improve station capacities during peak hours was developed. This strategy involves the use of a cascade of tubes in the tube trailers, wherein hydrogen gas is consolidated into one tube during peak fueling times. The high-pressure tube is then used directly for vehicle fueling while the compressor is used to either

pressurize the gas in the other tubes or replenish buffer storage. This technique reduces on-site compression requirements, enabling a 10-kg/hr compressor to serve a 450-kg/day station, three times the capacity of 150 kg/day it could otherwise serve, that results in a 14% cost reduction for tube trailer delivery from $3.30/gge to $2.85/gge delivered and dispensed for 700-bar refueling. (Argonne National Laboratory)

- A Phase II award of $1M for the FY 2013 Small Business Innovation Research topic on hoses for hydrogen dispensing at 700 bar was made to Nanosonic Inc. The project objective is to develop a low-cost hose for dispensing hydrogen that can be operated reliably for more than 25,000 fuelings under the temperature and pressure cycles (-40°C and 875 bar) experienced during fueling of 700-bar tanks to the SAE J2601 type A fill. During phase I, the project selected polymers for hose construction that survived the low-temperature flexure test and exhibited ultra-low hydrogen permeance after severe bending. The team then used these materials to form hoses that were predicted to have burst pressures of 2,560 bar. During phase II, hoses made of the selected materials will be evaluated per American National Standards Institute/CSA HGV 4.2-2013 to verify their safety, compatibility for hydrogen service, and weatherability. (Nanosonic Inc.)
- A $150K Small Business Innovation Research award was made to GVD Corporation for the development and testing of a novel coating for plastic/elastomer seals used in hydrogen technologies. Seals have poor reliability and high cost because of their failure rates in extreme temperatures and high-pressure hydrogen. GVD's coating, which will be comprised of both inorganic and organic layers that will be generated by chemical vapor deposition technologies, will reduce hydrogen permeation into the seal by 10x over the uncoated baseline. (GVD Corporation)

BUDGET

The FY 2014 appropriation provided $21 million for the Hydrogen Production and Delivery sub-program, with approximately $9.7 million provided for Delivery RD&D. The estimated budget breakdown for Delivery in FY 2014 and FY 2015 is shown below. The request for Hydrogen Production and Delivery in FY 2015 is $21 million, with $11 million planned for Delivery RD&D, with an emphasis on reducing near-term technology costs, improving forecourt compressor reliability, and reducing onsite storage costs.



* Subject to appropriations, project go/no-go decisions, and competitive selections. Exact amounts will be determined based on research and development progress in each area.

FY 2015 PLANS

In FY 2015, the Hydrogen Delivery sub-program will focus on several key efforts:

- Release an updated version of the Hydrogen Delivery Scenario Analysis model. The results of a May 2014 Independent Panel Review Report on the current status of compression, storage, and dispensing technologies will be used to revise and release an updated version of the Hydrogen Delivery Scenario Analysis model by the end of 2014. The new version will include updated 700-bar and cryo-compressed dispensing scenarios from liquid hydrogen delivery, as well as updated cost indices.
- Complete data analysis and reporting to ASME B31.12 for inclusion of FRP into the code. The initial proposal for codification of FRP pipeline into ASME B31.12 was presented to the Code Committee in March 2014. Additional research is currently being conducted at SRNL to support codification. Fatigue testing is being conducted to support a 50-year design life for FRP, and non-mechanical joints are being evaluated. A demonstration of FRP in hydrogen service is also planned.
- Validate the steel concrete composite vessel cost and performance, through prototype testing, to demonstrate that it meets the 2015 cost and performance targets in the Multi-Year Research, Development, and Demonstration Plan.
- Continue to focus on forecourt RD&D through new awards and the H2FIRST project. H2FIRST is composed of many interdisciplinary initiatives to support early market infrastructure deployment. Specific efforts will include technoeconomic modeling of station requirements and market demands, and the development, optimization, and validation of technologies that address barriers to station operation and integrate hydrogen infrastructure to the electric grid.

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