III.0 Hydrogen Delivery Sub-Program Overview

INTRODUCTION

The Hydrogen Delivery sub-program supports research and development (R&D) of technologies that enable low-cost, efficient, and safe delivery of hydrogen to the end-user in order to achieve a threshold cost of \$2–\$4 per gallon gasoline equivalent (gge) of hydrogen (produced, delivered, and dispensed), which represents the cost at which hydrogen fuel cell electric vehicles (FCEVs) are projected to become competitive on a cost-per-mile basis with competing vehicles (gasoline-powered hybrid-electric vehicles) in 2020.[1] The Hydrogen Delivery sub-program addresses all hydrogen distribution activities from the point of production to the point of dispensing. R&D activities address challenges to the widespread adoption 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 technologies. Strategic analysis is used by the sub-program to identify cost, performance and market barriers to commercial deployment of hydrogen technologies, and to inform 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[2]

The key objective of this sub-program is to develop low-cost, efficient, and safe technologies for delivering hydrogen from the point of production to the point of use-including stationary fuel cells and FCEVs. This objective applies to all of the possible delivery pathways. Interim and ultimate targets for various delivery components are being updated in the *Fuel Cell Technologies Program Multi-Year Research, Development, and Demonstration Plan (MYRD&D Plan)*. Key objectives for specific delivery components include:

- **Tube Trailers:** Reduce the cost of compressed gas delivery via tube trailer by increasing vessel capacity and lowering trailer cost on a per-kilogram-of-hydrogen-transported basis.
- **Pipeline Technology:** Develop mitigation strategies for combined material fatigue and hydrogen-induced embrittlement in steel pipelines; advance the development and acceptance of alternative composite pipe materials that can reduce installed pipeline costs; and develop lower-cost, higher-reliability compression technology for hydrogen transmission by pipeline.
- **Liquefaction:** Reduce the capital and operating costs of hydrogen liquefiers and bulk liquid storage vessels.
- **Forecourt Technologies:**
  - Compression: Develop lower-cost, higher-reliability hydrogen compression technology for terminal and forecourt applications.
  - Storage: Develop lower-capital-cost off-board bulk storage technology.
- **Analysis:** Conduct comprehensive analyses on potential near- and longer-term hydrogen delivery options, comparing the relative advantages of each and examining possible transition scenarios between the two timeframes.

[1] Hydrogen Threshold Cost Calculation, Hydrogen and Fuel Cells Program Record #11007, US Department of Energy, 2012, http://www.hydrogen.energy.gov/pdfs/11007_h2_threshold_costs.pdf
[2] Note: Targets and milestones were recently revised; therefore, individual project progress reports may reference prior targets. Some targets are still currently under revision, with updates to be published in Fiscal Year (FY) 2013.

FY 2012 STATUS AND PROGRESS

In FY 2012 the Delivery sub-program published updated hydrogen delivery scenario analysis models (HDSAM) version 2.3 and version 2.3.1. In addition, updated cost and performance targets for delivery technologies were developed and published in the Delivery chapter of the *MYRD&D Plan*, which was released in September 2012. The Delivery chapter is organized by technology pathway: tube trailers and bulk storage, pipeline technology, and forecourt technology, followed by pathway analysis work.

The projected 2011 costs for the delivery of hydrogen by currently available technologies range from \$2.50/gge to \$9/gge, depending on the quantity and distance transported.[3] These projections include the costs of compression, storage, and dispensing at the refueling site and are based on HDSAM assumptions. In order to achieve the threshold cost of \$2–\$4/gge, the goal of the Delivery sub-program is to reduce the delivery cost of hydrogen to <\$2/gge by 2020.[4] Progress towards current goals and targets to achieve this ultimate goal are summarized in Table 1.

TABLE 1. Delivery Targets and Status

Delivery Element	Targets (2015/2020)[5]	Status[5]
Tube Trailers	Reduce capital cost to <\$728/kg by 2015 and <\$574/kg by 2020 Increase capacity to 700 kg by 2015 and 940 kg by 2020	Capital cost: \$510/kg Capacity: 726 kg
Pipelines	Reduce cost/mile (8 in. diameter pipe installed) to <\$735,000 by 2015 and <\$710,000 by 2020	Installed steel pipeline cost: \$3 million/mile Cost contribution: \$1.7/kg H_2 Compressor cost contribution: \$0.1/kg H_2
Forecourt Compression (1,000 kg/day station)	Reduce uninstalled capital cost to \$400K/\$240k for 700 bar dispensing	Capital cost: \$530K for 700 bar compression
Pipeline Compression	Reduce the uninstalled capital cost for 3,000-kW compressor to <\$2.3 million by 2015 and <\$1.9 million by 2020	Capital cost: \$2.7 million
Forecourt Storage (1,000 kg/day station)	Reduce high pressure tank cost to \$1,200 per kg of stored H_2 by 2015 and \$1,000 by 2020	Storage tank cost: \$1,450 per kg of stored H_2

Tube Trailers and Bulk Storage

Tube trailers and bulk storage are a critical near-term technology. Until there is significant expansion of the hydrogen pipeline infrastructure, truck transport and storage at the forecourt will be the primary means of distribution to fueling stations. In the last decade, the hydrogen-carrying capacity of tube trailers has more than doubled and the per-kilogram cost has fallen more than 40%. This year, Lincoln Composites was able to further improve on this progress.

- A custom-built trailer shown in Figure 2 capable of holding four 40-foot pressure vessels and an additional 30-foot pressure vessel was designed and constructed. This new design has the potential to increase overall capacity by roughly 18% from about 615 kg in the current Department of Transportation-approved design to more than 725 kg. A prototype trailer (minus vessels, plumbing, and fire protection) was received this year. (Lincoln Composites)
- Pathways were identified for steel-lined reinforced-concrete hydrogen pressure vessels to achieve the DOE 2020 cost target through development of advanced vessel manufacturing technology and materials.

[3] *Hydrogen Delivery Cost Projections*, Hydrogen and Fuel Cells Program Record #12022, U.S. Department of Energy, under review in 2012.
[4] *Hydrogen Production and Delivery Cost Apportionment*, Hydrogen and Fuel Cells Program Record #12001, U.S. Department of Energy, under review in 2012.
[5] *Fuel Cell Technologies Program MYRD&D Plan* (Section 3.2, *Hydrogen Delivery*), U.S. Department of Energy, September 2012, www.hydrogenandfuelcells.energy.gov/mypp/index.html.

Feasibility of multi-pass, multi-layer friction-stir welding for steel vessel fabrication was demonstrated by successfully joining a 15-mm-thick (0.6 in.) steel plate, which nearly tripled the thickness of steel that can be welded by the conventional friction-stir welding. (Oak Ridge National Laboratory)

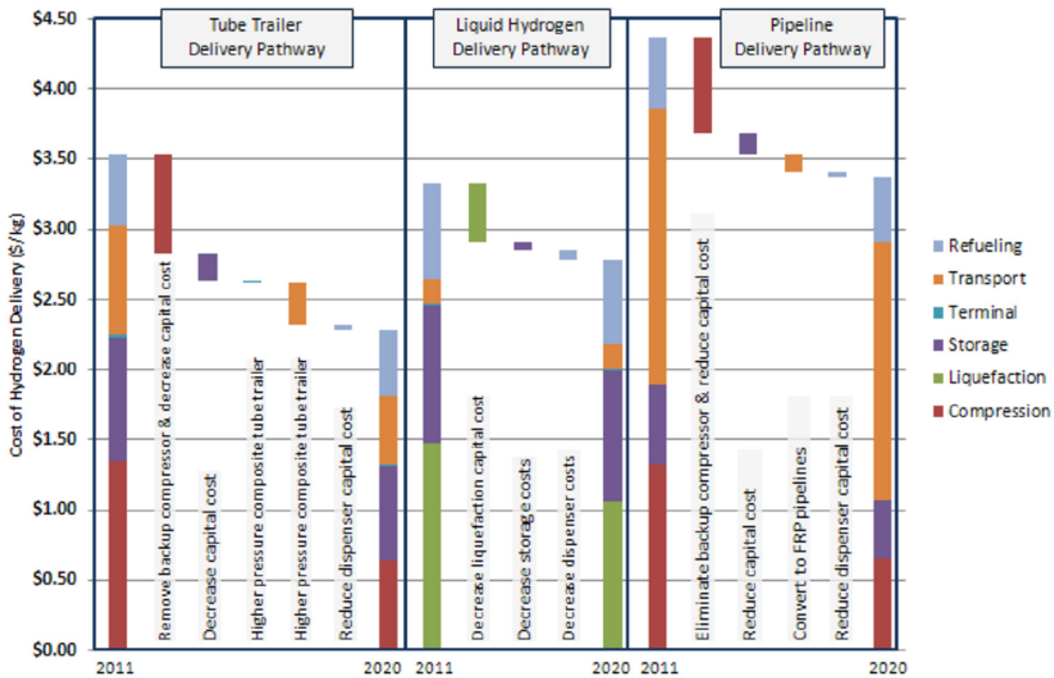


FIGURE 1. This chart shows the projected reduction in hydrogen delivery cost for various pathways based on preliminary analysis (FY 2011–FY 2012) due to technological advancement. Projections are based on HDSAM V2.31 for a well-established hydrogen market demand for transportation (10% market penetration). The specific scenarios examined assume central production of hydrogen that serves a city of moderately large size (population of about 1.5 million).

FIGURE 2. Lincoln Composites carbon fiber composite tube trailer pressure vessel and International Organization for Standardization container.

Pipeline Technologies

Pipeline technologies will enable the low-cost delivery of hydrogen in the future. Progress in both the characterization and development of pipeline materials and centrifugal pipeline compressors has been achieved through projects funded by the Hydrogen Delivery sub-program. Testing of fiber-reinforced polymer materials for pipelines is facilitating the adoption of these materials for hydrogen service applications by providing performance data to inform the development of the codes and standards needed for their commercial use. In the area of centrifugal compression, advanced seals have been developed which allow for the compression of hydrogen. Specific accomplishments for this year include:

- Fatigue testing for both flawed and unflawed samples of fiber-reinforced polymer pipe was completed to address the effects of third-party damage. The 40% through-wall flaws resulted in a 28% lower burst pressure of the flawed samples than the unflawed samples. (Savannah River National Laboratory)
- A physics-based model for accelerated fatigue crack growth of steels in hydrogen gas with oxygen impurities was developed. This model enables the extrapolation of data over a range of hydrogen pressure, oxygen concentration, load-cycle frequency, and load ratio (R_K). The model also demonstrates that the threshold level of oxygen required for mitigating accelerated fatigue crack growth of X52 steel in 21 MPa hydrogen gas is a function of load-cycle frequency and R_K. (Sandia National Laboratories)
- The fabrication, assembly and validation testing of a single-stage, oil-free centrifugal pipeline compressor system (Figure 3) was completed, and initial validation tests were performed at 30,000 rpm. The system, which includes advanced Ti-based rotors to achieve the tip speeds needed to meet DOE's 2015 targets for pipeline compression technology, will be tested in FY 2013 at 60,000 rpm in a dedicated test cell currently under construction. (Mohawk Innovative Technology)

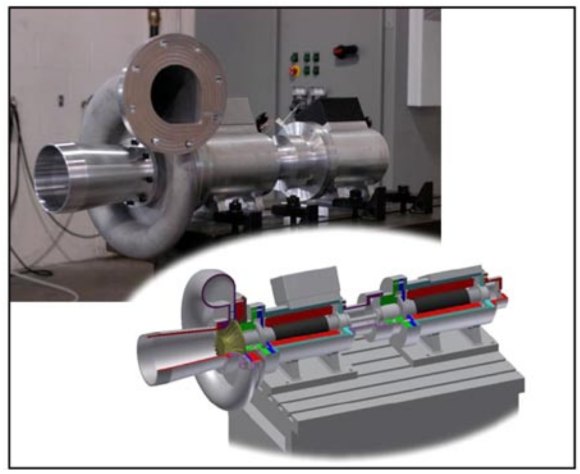


FIGURE 3. MiTi single-stage compressor driven by two 100-kW oil-free motors.

Forecourt Technologies

Improvements in the reliability and cost of forecourt compression and dispensing technologies are needed for the commercialization of hydrogen technologies. Cost improvements can be realized through efficiency improvements and reliability improvements as well as through new designs and materials. Progressive technologies in this area include electrochemical compression and liquid ionic compression. Recent progress includes:

- The maximum hydrogen pressure from a single-stage electrochemical compressor was increased to 12,800 psi (880 bar) from 7,000 psi (480 bar), and at the same time, 98% hydrogen recovery was achieved in a single cell. A 6,000-hour life at an elevated current density of 750 mA/cm^2 (as compared with 200 mA/cm^2) was also demonstrated. (FuelCell Energy)

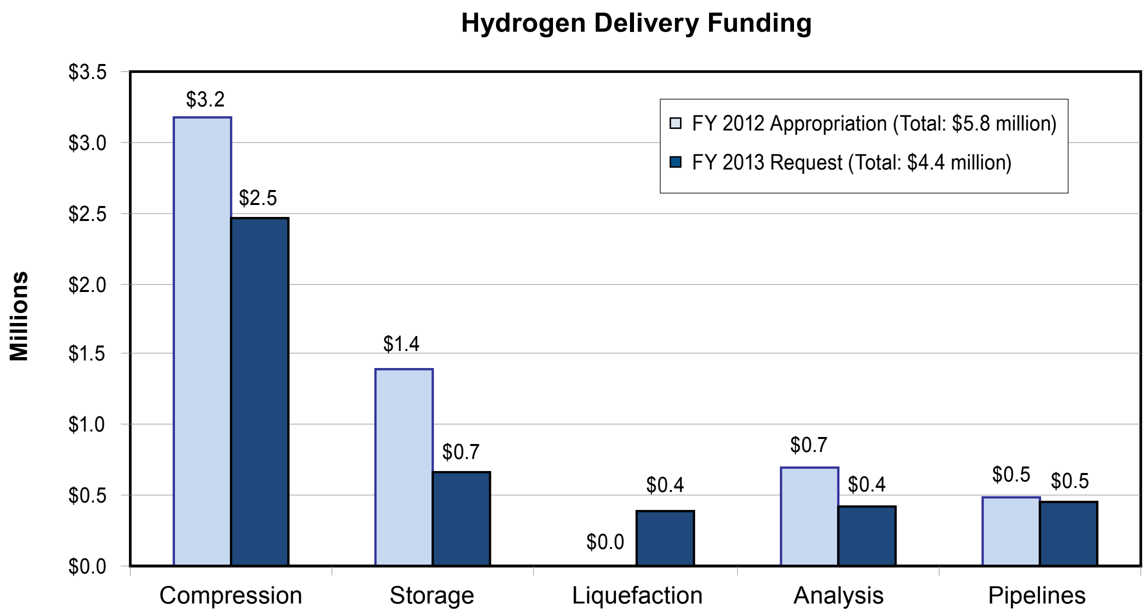
Analysis

Analysis efforts continue to identify areas in most critical need of R&D advances. Additionally, analysis is used to optimize technology pathways in order to reduce the final as-dispensed cost of hydrogen. Progress this year included evaluation of the current cost and power requirement of refueling station compression and pumping technologies and various configurations of high-pressure tube-trailers (within U.S. Department of

Transportation–specified weight and size constraints, including tube fill pressure, tube diameter/thickness, number of tubes and tube material). Two compression options to reduce station capital cost by at least 15% were identified: (1) a high-pressure (900-bar) liquid pump to increase pressure, combined with an evaporator to gasify the hydrogen before dispensing (the combined pump/vaporizer cost is more than 50% lower than the corresponding gas compressor cost); and (2) a high-pressure tube trailer, which can reduce compression demand at the station, especially in early markets where the utilization of the station compressor capital is low (this has the potential to reduce the impact of station capital cost on overall hydrogen cost by up to 20%, assuming 50% utilization). (Argonne National Laboratory)

BUDGET

The FY 2012 appropriation provided $5.8 million for the Hydrogen Delivery sub-program, and $4.4 million is planned for FY 2013 (based on the President's budget request), with an emphasis on reducing near-term technology costs, increasing tube trailer capacity, and lowering the cost of pipeline delivery pathways.



FY 2013 PLANS

In FY 2013, the Hydrogen Delivery sub-program portfolio will focus on two key areas:

1. *Long-term technologies expected to have market impact in 10–20 years.* In FY 2013, the Delivery sub-program portfolio will continue efforts on technologies for transmitting hydrogen as a cold, pressurized fluid—including magnetic refrigeration and electrochemical compression. Some work will also continue on the testing and characterization of materials and systems for pipelines and pipeline compression; however, with the decreased funding scenario, more emphasis will be given to near-term technologies that can have an immediate impact.
2. *Near-term technologies that reduce hydrogen delivery costs for emerging hydrogen and fuel cell applications (e.g., forklifts and backup power) and early adopter FCEV markets.* In FY 2013, the emphasis will be on development of delivery options to reduce the cost of 700-bar hydrogen compression at light-

duty vehicle refueling stations, and on identification of material needs and challenges for delivery and forecourt technologies. New projects in FY 2013 will address technologies to reduce station costs and improve the reliability of forecourt compression and dispensing technologies.

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