III.0 Hydrogen Delivery Sub-Program Overview

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. Activities include the development of technologies required for hydrogen transport, either as a liquid (in tanker trucks) or as a compressed gas (in pipelines or tube trailers). Cost-effective methods of transporting hydrogen from central production facilities are required to achieve sustainable, widespread commercialization of hydrogen fuel cells. In addition, there are several activities within the Delivery sub-program focused on developing innovative methods of compressing, storing, and dispensing hydrogen at the point of refueling. Advances in these technologies will facilitate reductions in the cost of hydrogen that is produced at both centralized and distributed facilities

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[1]

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 fuel cell electric vehicles (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's *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 and confirm the technical feasibility of geologic storage for hydrogen.
- **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.

Fiscal Year (FY) 2011 Technology Status

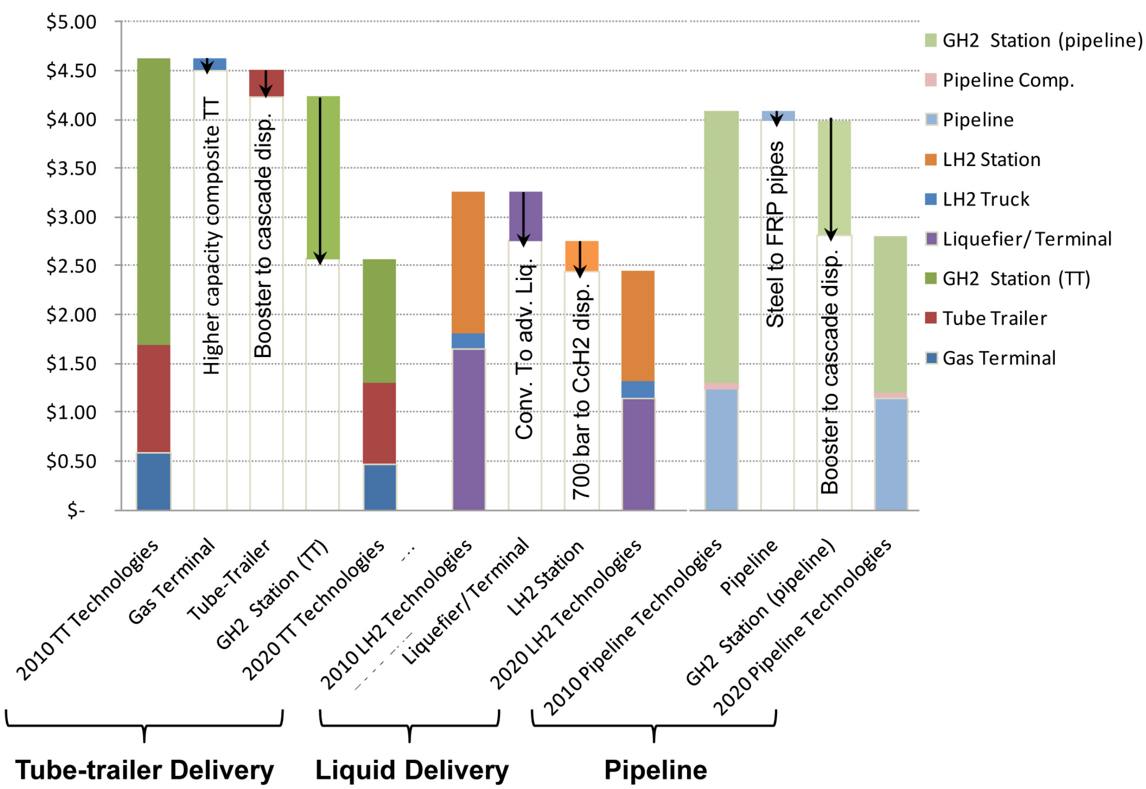
The projected costs for the delivery of hydrogen, based on current technologies, range from $3/gasoline gallon equivalent (gge) to $10/gge, depending on the quantity and distance transported. These projections include the costs of compression, storage, and dispensing at the refueling site. Progress towards current goals and targets is summarized in the following table.

[1] Note: Targets and milestones are under revision; therefore, individual progress reports may reference prior targets.

Delivery Element	Targets (2015/2017)[1]	Status[2]
Tube Trailers	• Reduce capital cost to <$200,000 • Increase capacity to 1,100 kg	• Capital cost: $470,000 (250 bar carbon fiber vessel) • Capacity: 550 kg • Cost contribution: $0.9/kg H_2
Pipeline Technology	• Reduce cost/mile (installed) to <$490K	• Installed steel pipeline cost: $3M/mile • Cost contribution: $1.7/kg H_2 • Compressor cost contribution: $0.1/kg H_2
Liquefaction	• Reduce installed capital cost to $100M • Increase energy efficiency to 87%	• Installed capital cost: $170M • System efficiency: 80% • Cost contribution: $1.6/kg H_2
Forecourt Compression (1,000 kg/day station)	• Reduce installed capital cost to $187.5K for 700 bar dispensing	• Capital cost: $1.5M for 700 bar dispensing (cost contribution of $2/kg H_2) • Capital cost $0.5M for 350 bar dispensing (cost contribution of $0.8/kg H_2)
Forecourt Storage (1,000 kg/day station)	• Reduce tank cost stored to $300 per kg of stored H_2	• Storage tank cost: $1,000 per kg of stored H_2 (cost contribution of $0.4/kg H_2)

[1] Based on current targets in the Fuel Cell Technologies Program's *MYRD&D Plan*. These are in the process of being updated.
[2] High-volume projections based on HDSAM version 2.3 (preliminary analysis; peer review underway).

Figure 1 shows the projected reduction in hydrogen delivery cost for various pathways due to technological advancement.



TT - tube trailer; GH2 - gaseous hydrogen; LH2 - liquefied hydrogen

FIGURE 1. Projected Reductions in Hydrogen Delivery Costs. Projections are based on Hydrogen Delivery Scenario Analysis Model (HDSAM) V2.3 for a well-established hydrogen market demand for transportation (15% market penetration). The specific scenarios examined assume central production of hydrogen that serves a city of moderately large size (population of about 1.2 million).

FY 2011 Accomplishments

Tube Trailers and Bulk Storage

- Lincoln Composites completed a design trade study for a 5,000 pounds per square inch (psi) vessel, which includes a projected 33% increase in capacity at 15°C and ~10% reduction in capital cost on a per kilogram of transported hydrogen basis.
- Lawrence Livermore National Laboratory scaled up their design of a glass fiber pressure vessel to a full diameter of 23 inches and successfully hydroburst tested the vessel at strains above trailer design levels. The concept has the potential to reduce current tube trailer transport costs by up to 50% (Figure 2).

FIGURE 2. Carbon Fiber Composite Tube Trailer Pressure Vessel and International Standards Organization Container

Pipeline Technology

- Savannah River National Laboratory completed burst testing on fiber reinforced polymer pipe with 40% through-wall flaws, demonstrating a 3x margin above the rated pressure for the pipe. Researchers also demonstrated that industry-standard compression fittings will meet Department of Transportation requirements for joint leakage between pipe segments.
- Fatigue crack growth relationships determined by Sandia National Laboratories for X52 base metal and electric resistance welded seam specimens cut from actual pipeline were found to be quite similar, despite some variability in replicate data sets. The results indicate that the reliability and integrity of steel hydrogen pipeline likely will not be determined by the properties of the electric resistance welded seam.
- Concepts ETI completed the detailed design of a centrifugal compressor capable of providing 240,000 kg/day of hydrogen at 1,280 psi for pipeline-grade service and have initiated procurement of the major gearbox components for fabrication and testing. Mohawk Innovative Technology also completed the design of a centrifugal pipeline compressor that will employ advanced Ti-based rotors to achieve the tip speeds needed to meet the DOE's 2015 targets for this technology (Figure 3). They are currently fabricating components for initial laboratory testing.

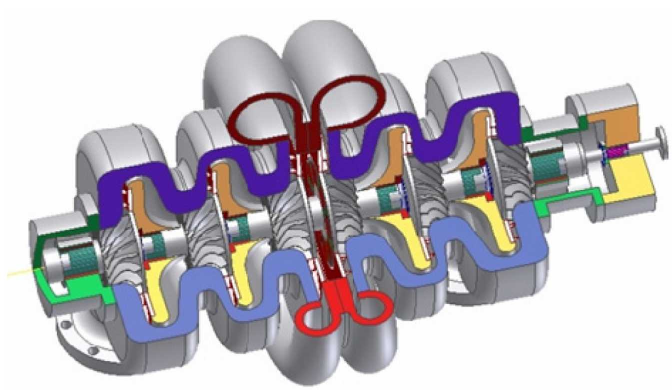


FIGURE 3. Double-Entry Centrifugal Compressor for Pipeline Compression

Liquefaction

- Praxair Inc. demonstrated a reduction in overall power consumption of ~2.5% by developing and employing a new ortho-para catalyst in the high-temperature heat exchanger of a traditional hydrogen liquefier design. Additionally, results from process modeling indicated that improved gas compression technology for these units can increase overall liquefier efficiency by 3%–6%.
- Prometheus Energy integrated all of the subsystems for their Phase-I linear active magnetic regenerative liquefier and demonstrated a sustainable magneto-thermal based reduction in temperature from 290 K to 120 K. Lessons learned are being applied to a Phase-II rotary design that will span 290 K to 20 K (Figure 4).

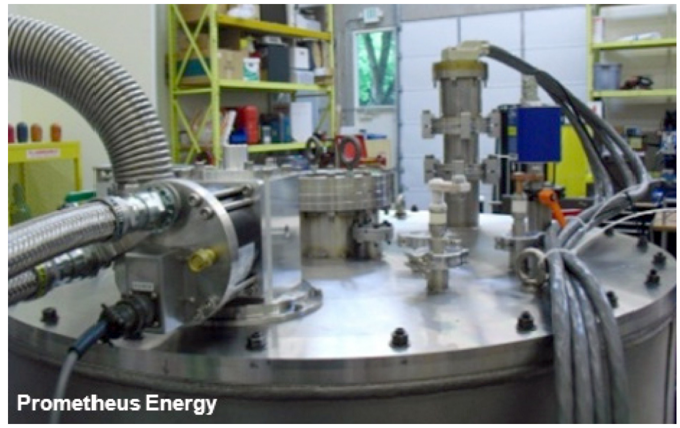


FIGURE 4. Active Magnetic Regenerative Refrigerator for Hydrogen Liquefaction

Forecourt Technology

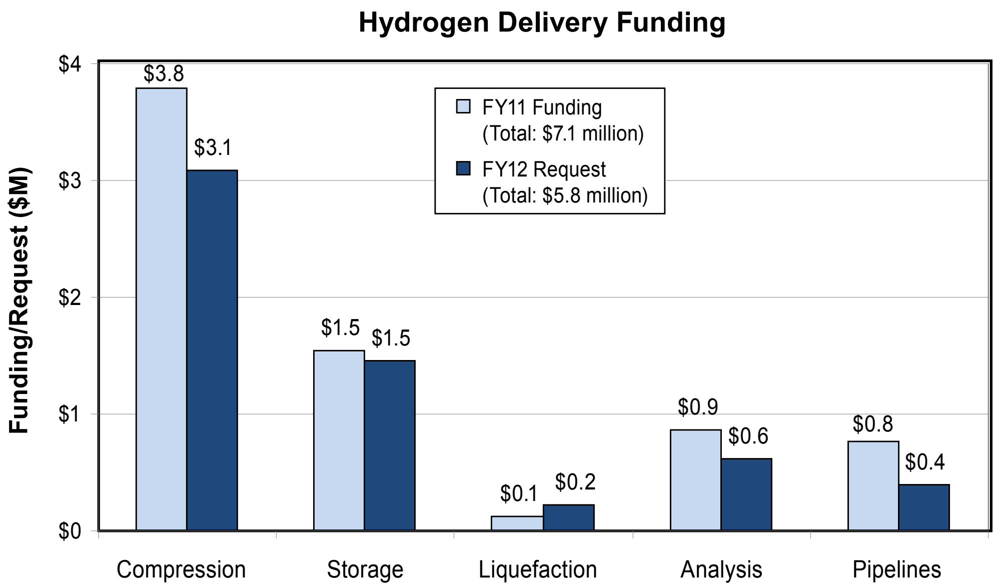
- FuelCell Energy developed a two-stage electrochemical hydrogen compressor that achieved 420 bar of compression, or a compression ratio of 300:1. To date, they have demonstrated 20 successful pressure cycles and 500 hours of durability with the device. They will be fabricating the support facilities to test this compressor to the ultimate pressure capability target of 840 bar.
- Conceptual designs for a steel-lined reinforced concrete hydrogen pressure vessel were completed at Oak Ridge National Laboratory. Preliminary cost estimates indicate that this concept has the potential to meet DOE's 2015 cost target for off-board bulk hydrogen storage.

Analysis

- Argonne National Laboratory completed cost and price index updates to HDSAM, evaluated factors affecting the capital and levelized cost of refueling stations, and carried out an analysis of key hydrogen infrastructure cost drivers in preparation for the sub-program's revised section of the *MYRD&D Plan*.
- Pacific Northwest National Laboratory completed a detailed analysis of pipeline costs, which was integrated into the updated HDSAM model.
- The National Renewable Energy Laboratory completed an analysis of hydrogen delivery by rail, finding this option to be the least costly means of transporting hydrogen over distances of more than 600 miles for early market scenarios–for example, when hydrogen is produced by renewable resources that are far from large demand centers. An analysis of hydrogen production and delivery costs from wind sources at remote, low-electricity-cost locations was also completed. It was found that under certain scenarios this option can provide dispensed hydrogen at a cost as low as $6/kg.

Budget

The FY 2011 budget provided $7.1 million for continued hydrogen delivery R&D. The President's FY 2012 budget request for the Office of Energy Efficiency and Renewable Energy provides $5.8 million for hydrogen delivery, with an emphasis on reducing pipeline and forecourt compression cost, increasing tube trailer capacity, and identifying viable low-cost early-market delivery pathways.



FY 2012 Plans

In FY 2012, the Delivery sub-program portfolio will be focused on two key areas:

1. **Long-term technologies expected to have market impact in 10–20 years.** In FY 2012 the Delivery sub-program portfolio will continue efforts on fiber reinforced polymer pipeline characterization for design code development; centrifugal compressor development and demonstration for pipeline transmission; hydrogen transmission as a cold, pressurized fluid; magnetic refrigeration; and electrochemical compression. Recognizing that hydrogen storage on-board future FCEVs may not be in the form of compressed gas (as is current practice) the Delivery and Storage sub-programs will collaborate to identify delivery challenges for future materials-based storage technologies. Analysis efforts will be initiated to evaluate options for the transition from compressed gas stations serving early vehicle markets to stations that could provide hydrogen for next generation FCEVs.
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 2012, the emphasis in these near-term areas will be on strategic analyses to: (a) determine delivery options that can reduce the cost of 700-bar compression at light-duty-vehicle refueling stations; (b) evaluate hydrogen delivery costs for sustainable non-automotive markets and establish possible "lessons learned" that can be applied to early localized FCEV markets; and (c) identify station costs not related to process operations (e.g., insurance and safety system requirements) and potential market incentives that can drive business decisions on station construction. Results from these analyses will be used to identify barriers for early market technologies and to help focus subsequent technology development efforts. A key FY 2012 Program milestone will be to identify delivery pathway(s) that can achieve a current, as-dispensed (350 bar) hydrogen cost of <$4/gge. Additional near-term R&D will include work to increase the hydrogen carrying capacity of current composite tube trailer designs by 15% or more and continued development of steel-lined reinforced concrete pressure vessels for station storage.

Sara Dillich
Hydrogen Production & Delivery Team Lead (Acting)
Fuel Cell Technologies Program
Department of Energy
1000 Independence Ave., SW
Washington, D.C. 20585-0121
Phone: (202) 586-7925
E-mail: Sara.Dillich@ee.doe.gov

K. Scott Weil
Hydrogen Delivery Team
Chief Scientist, Pacific Northwest National Laboratory
On assignment to the Fuel Cell Technologies Program
Department of Energy
1000 Independence Ave., SW
Washington, D.C. 20585-0121
Phone: (202) 586-1758
E-mail: Kenneth.Weil@ee.doe.gov