

## IV.A.2 Hydrogen Storage Cost Analysis

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### Subcontractors:

- Argonne National Laboratory (ANL), Argonne, IL
- Pacific Northwest National Laboratory (PNNL)  
Richland, WA

Project Start Date: October 1, 2016  
Project End Date: September 30, 2020

### Overall Objectives

- Identify and/or update the configuration and performance of a variety of H<sub>2</sub> storage systems for both vehicular and stationary applications.
- Conduct rigorous cost estimates of multiple H<sub>2</sub> storage systems to reflect optimized components for the specific application and manufacturing processes at various rates of production.
- Explore cost parameter sensitivity to gain understanding of system cost drivers and pathways to lowering system cost.

### Fiscal Year (FY) 2017 Objectives

- Assess the cost and performance of cryo-compressed (CCH<sub>2</sub>) for onboard fuel cell electric bus (FCEB) H<sub>2</sub> storage.
- Assess the impact of alternative linker chemistries on the high-volume cost of metal organic framework (MOF) H<sub>2</sub> storage materials.
- Investigate potential cost savings of cold compressed H<sub>2</sub>.
- Establish a baseline cost for Type IV compressed natural gas (CNG) storage in support of the Institute for Advanced Composite Manufacturing Innovation.

### Technical Barriers

This project addresses the following technical barriers from the Hydrogen Storage section of the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan.

- (B) System Cost
- (H) Balance of Plant (BOP) Components
- (K) System Life-Cycle Assessments

### Technical Targets

This project conducts cost modeling to attain realistic, process-based system costs for a variety of H<sub>2</sub> storage systems, helping to inform progress towards meeting the DOE 2020 and ultimate technical targets for hydrogen system storage cost and performance.

- System storage cost: \$10/kWh (2020), \$8/kWh (Ultimate)
- Specific energy: 1.8 kWh/kg (2020), 2.5 kWh/kg (Ultimate)
- Energy density: 1.3 kWh/L (2020), 2.3 kWh/L (Ultimate)

### FY 2017 Accomplishments

- Completed a preliminary cost analysis of CCH<sub>2</sub> onboard H<sub>2</sub> storage systems for FCEB applications (40 kg usable H<sub>2</sub>) based on performance analysis by ANL and system design from Lawrence Livermore National Laboratory (LLNL).
- Completed an analysis of factory costs of MOF-74 based on alternative, low-cost linkers development and tested at Lawrence Berkeley National Laboratory.
- Completed an initial assessment of potential carbon fiber composite savings for Type 3 and Type 4 pressure vessels as a function of H<sub>2</sub> temperature and pressure.
- Completed a baseline analysis of CNG tank cost for 3,600 psi natural gas storage in Type 4 pressure vessels for light-duty and heavy-duty onboard storage.



### INTRODUCTION

The Fuel Cell Technologies Office has identified H<sub>2</sub> storage as a key enabling technology for advancing H<sub>2</sub> and fuel cell technologies and has established goals of developing and demonstrating viable H<sub>2</sub> storage technologies

for transportation and stationary applications. The cost assessment described in this report supports the overall Fuel Cell Technologies Office goals by identifying the impact of advances in components, performance levels, and manufacturing/assembly techniques on storage system cost at a variety of annual manufacturing rates. The results of this analysis enable the DOE to compare the cost impact of new components, etc., to the intermediate and ultimate DOE cost targets. The cost breakdown of the system components and manufacturing steps can then be used to guide future research and development decisions.

## APPROACH

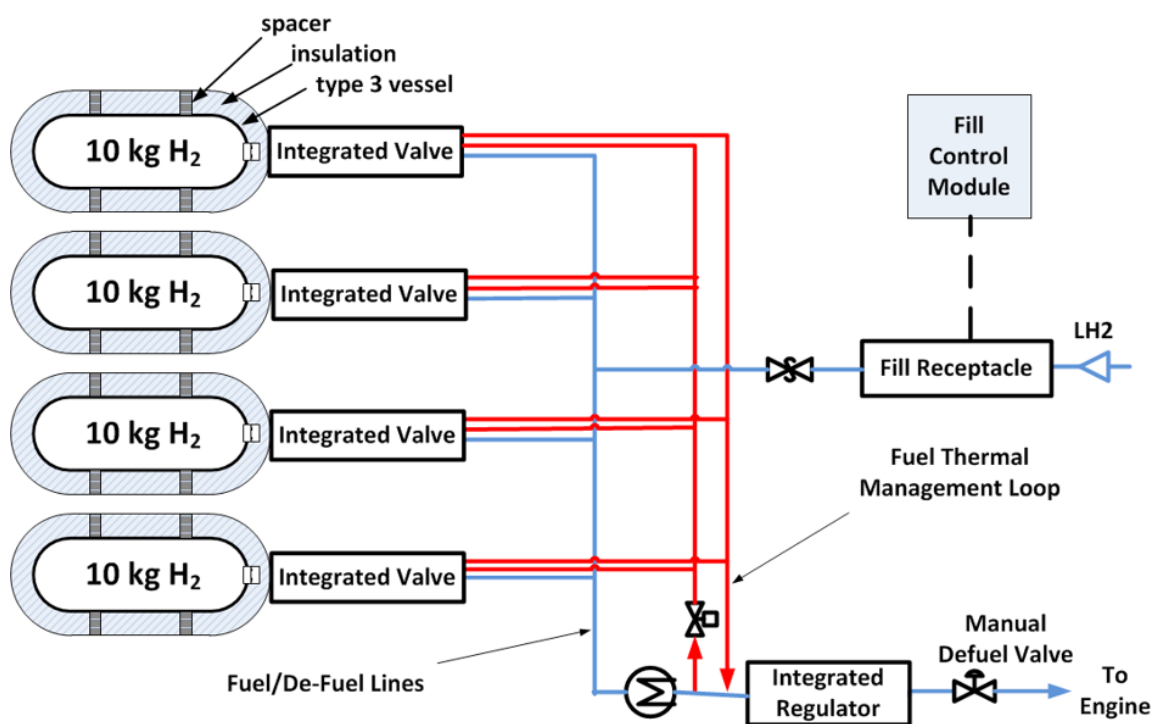
A Design for Manufacture and Assembly (DFMA<sup>®</sup>) style cost analysis methodology was used to assess the materials and manufacturing cost of hydrogen storage systems and components. Key system design parameters and engineering system diagrams describing system functionality and postulated manufacturing process flows were obtained from a combination of industry partners, ANL, PNNL, and internal analysis. This data was used to develop a mechanical design of each component, including materials, dimensions, and physical construction. Based on this design, the manufacturing process train was modeled to project the

cost to manufacture each part. Cost was based on the capital cost of the manufacturing equipment, machine rate of the equipment, equipment tooling amortization, material costs, and financial assumptions. Once the cost model was complete for the system design, sensitivity data for the modeled technology was obtained by varying key parameters. Results were shared with ANL, PNNL, and industry partners to obtain feedback and further refine the model.

The analysis explicitly includes fixed factory expenses such as equipment depreciation, tooling amortization, utilities, and maintenance as well as variable direct costs such as materials and labor. However, because this analysis is intended to model manufacturing costs, a number of components that usually contribute to the original equipment manufacturer price are explicitly not included in the modeling. The following costs are excluded in this analysis: profit and markup, one-time costs for non-recurring research/design/engineering expenses, and general expenses such as general and administrative costs, warranties, advertising, and sales taxes.

## RESULTS

**Cryogenic H<sub>2</sub> storage:** Cryogenic H<sub>2</sub> storage for FCEBs was investigated this year. A system diagram is shown in Figure 1 and system assumptions are summarized in Table 1.



**FIGURE 1.** System schematic of a 40 kg H<sub>2, usable</sub> cryo-compressed storage system for FCEB applications. Integrated valves are external to the outer containment vessels and each one includes an inline filter, temperature transducer, pressure transducer, thermal pressure relief device, solenoid valve, and excess flow valve. The single integrated regulator includes a two-stage pressure regulator, pressure transducer, pressure relief valve, and an automatic shut-off valve. The fill control module has data communication lines connecting to the in-valve temperature and pressure transducers and the fill receptacle to communicate fill status to the fill station nozzle.

**TABLE 1.** System Parameters for CcH<sub>2</sub> Storage System with 40 kg Usable H<sub>2</sub> for FCEB Applications

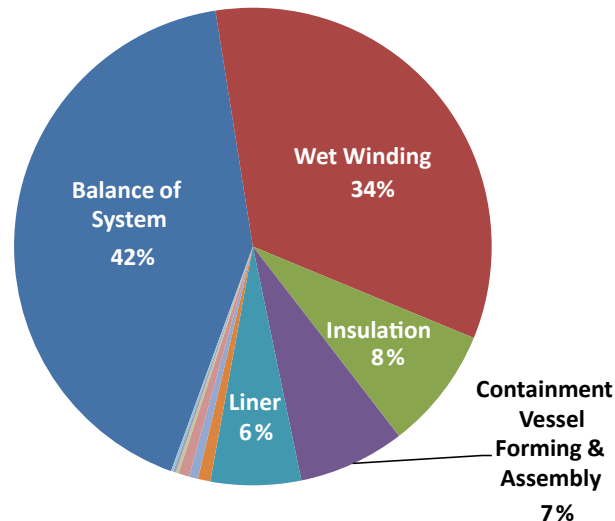
Design Parameter	Base Case Value	Basis/Comment
Rated Storage Pressure	500 bar	ANL modeling assumption
Burst Pressure	1,125 bar	2.25 safety factor per SAE J2579
Minimum (Empty) Pressure	5 bar	Minimum fuel cell delivery pressure
Storage Temperature Range	93–123 K	ANL modeling assumption
Tank Volume (Water Capacity)	169.1 L	ANL modeling assumption
Usable H <sub>2</sub>	10 kg	ANL modeling assumption
Pressure Vessel Dimension	176 cm x 35.2 cm	Internal length x diameter
Liner Thickness	2 mm	ANL modeling assumption
Carbon Fiber Type	T700S	ANL modeling assumption
Resin	Epoxy	ANL modeling assumption
Total Allowable Heat Leak	10 W	ANL modeling assumption
Insulation Thickness	7 mm	$K_{\text{eff}} = 5\text{E-}5 \text{ W/m-K}$ ; $\Delta Q_{\text{insulation}} \leq 3\text{W}$
Vacuum Pressure (design)	10 <sup>-3</sup> Torr	LLNL feedback
Liner Material	316L	ANL modeling assumption
Vacuum Gap	8.4 mm	120% of minimum insulation thickness

Preliminary analysis of the 40 kg CcH<sub>2</sub> system resulted in a cost of ~\$15/kWh when produced at 5,000 systems per year. A system cost breakdown at 5,000 systems per year is shown in Figure 2. The high balance of system cost (42%) reflects our current estimate that key components (regulator and valve) will be approximately twice as expensive as their ambient temperature counterparts as well as the additional complexity of thermal management associated with the cryogenic system.

Two main issues remain that lead to uncertainty in the system cost projection. First, balance of system components compatible with high pressure cryogenic H<sub>2</sub> are expected to be more expensive than similar components (e.g., regulator and valve) for 700 bar compressed H<sub>2</sub>. How much more expensive these components are at high manufacturing volume is not currently well understood. Preliminary analysis of the valve at low volume suggests that the cost is similar for both the 700 bar compressed H<sub>2</sub> and the 500 bar CcH<sub>2</sub>. Finally, the time to pump down the insulation gap can take up to one week for proto-type systems. We currently assume that the insulation gap can be pumped down in under 6 h.

**MOF synthesis:** In a paper authored by Strategic Analysis, Ford Motor Co., and Lawrence Berkeley National Laboratory, the cost of manufacturing MOFs at auto-relevant scale was estimated for traditional thermo-solvent methods, liquid assisted grinding (LAG), and aqueous solution synthesis [1]. Dramatic reductions in production cost are expected for alternative synthesis methods using little or no organic solvents (LAG and aqueous synthesis) and lead to MOF costs approaching \$10/kg MOF. One limitation of the

**500 bar CcH<sub>2</sub> System Cost  
Bus System, 40kgH<sub>2</sub>  
5,000 Systems/Year**

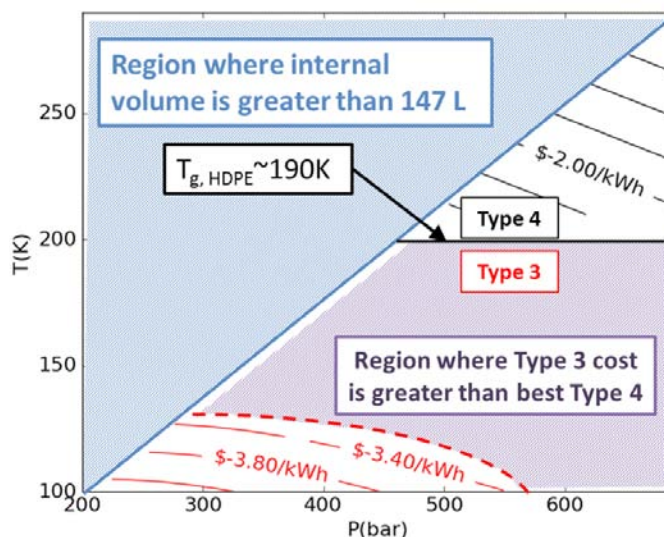


**FIGURE 2.** System cost breakdown for 40 kg H<sub>2,usable</sub> cryo-compressed storage system for FCEB applications manufactured at 5,000 systems per year.

published analysis was that linker material costs were poorly understood at the volumes studied. To better understand linker costs, a full DFMA<sup>®</sup> style analysis of linker cost was conducted for two isomers of the MOF-74 linker based on recently reported results [2].

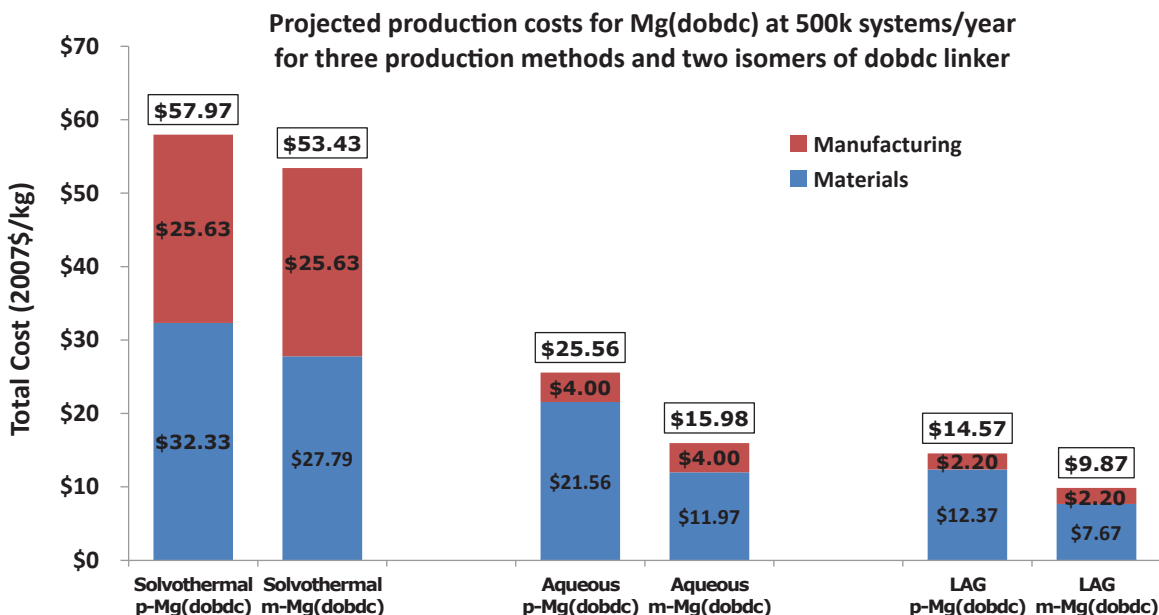
The two MOF-74 linker isomers, 2,5-dioxido-1,4-benzenedicarboxylate (p-dobdc) and 4,6-dioxido-1,3-benzenedicarboxylate (m-dobdc) are prepared from different starting materials, hydroquinone and resorcinol, respectively. Linker synthesis costs were modeled based on methods described in the literature for p-dobdc [3] and for m-dobdc [4]. Figure 3 summarizes the cost to manufacture MOF-74 at 25,000 tonnes annually (sufficient for 500,000 vehicles with 50 kg MOF-74 per vehicle). MOF-74 costs are compared for the two linkers (p-dobdc and m-dobdc) prepared by solvothermal synthesis, aqueous synthesis, and LAG. This analysis suggests that MOF-74 prepared via LAG is \$9.87/kg MOF using m-(dobdc) linker, and \$14.57/kg MOF using p-(dobdc) linker.

**Cold-compressed analysis:** Finally, a computational survey of cold- and cryo-compressed H<sub>2</sub> storage systems was conducted to explore the cost impact of various temperature and pressure storage combinations. Figure 4 maps out regions of tank cost in hydrogen state space relative to the baseline 700 bar, 298 K Type 4 compressed H<sub>2</sub> storage vessel. Figure 4 shows that storage at 500 bar, 200 K has the potential to save around \$3/kWh compared to the baseline pressure vessel at 700 bar and 298 K. Insulation and an outer containment vessel is estimated to add ~\$0.50/kWh leading to an estimated potential \$2.50/kWh savings for the pressure vessel.



T – temperature; P – pressure

**FIGURE 4.** Potential cost savings for composite overwrapped pressure vessel with high-density polyethylene (HDPE) and 316 L liners. Costs are reported as relative to ambient temperature 700 bar Type 4 pressure vessels. Contour lines show constant cost savings.



**FIGURE 3.** Comparison of production costs for MOF-74 (at 2,500 tonnes per year) for solvothermal, aqueous, and liquid assisted grinding using p-dobdc and m-dobdc linkers.

## CONCLUSIONS AND UPCOMING ACTIVITIES

- CcH<sub>2</sub> storage system
  - Completed preliminary analyses for bus and light-duty vehicles.
  - In future, will finalize the analysis and publish an updated assessment of the cost and performance of CcH<sub>2</sub> for both bus and light-duty vehicle applications.
- MOFs can be manufactured at a cost of <\$10/kg MOF using alternative linker materials and synthesis methods that minimize the use of organic solvents.
- Cold compressed H<sub>2</sub> (500 bar, 200 K) show promise to reduce system cost by ~\$2.5/kWh; full system cost analysis will be completed to fully account for additional system costs.
- A baseline cost assessment for Type IV CNG storage was delivered to the Institute for Advanced Composite Manufacturing Innovation.

## FY 2017 PUBLICATIONS/PRESENTATIONS

1. Brian D. James and Cassidy Houchins, “700 bar Type IV H<sub>2</sub> Pressure Vessel Cost Projections,” presented at the Department of Energy Physical-Based Hydrogen Storage Workshop, Southfield, MI, 24-Aug-2016.
2. Cassidy Houchins, Daniel D. DeSantis, Jarad A. Mason, Brian D. James, Jeffrey R. Long, and Mike Veenstra, “Techno-economic analysis of metal-organic frameworks for onboard hydrogen and natural gas storage,” presented at the 2016 AIChE Annual Meeting, San Francisco, CA, 16-Nov-2016.
3. D. DeSantis, J. A. Mason, B.D. James, C. Houchins, J.R. Long, and M. Veenstra, “Techno-economic analysis of metal-organic frameworks for hydrogen and natural gas storage,” *Energy Fuels*, Jan. 2017.
4. Brian D. James and Cassidy Houchins, “Hydrogen Storage Cost Analysis,” presented at the USCAR Hydrogen Storage Tech Team, Southfield, MI, 19-Jan-2017.
5. Brian D. James and Cassidy Houchins, “LDV and HDV CNG Storage System Analysis,” presented at the Presentation to AMO, IACMI, and FCTO, Washington, D.C., 20-Jan-2017.
6. Brian D. James and Cassidy Houchins, “Hydrogen Storage Cost Analysis,” presented at the 2017 DOE Hydrogen and Fuel Cells Program Review, Washington, D.C., 08-Jun-2017.

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1. DeSantis, Daniel, Jarad A. Mason, Brian D. James, Cassidy Houchins, Jeffrey R. Long, and Mike Veenstra, “Techno-Economic Analysis of Metal-Organic Frameworks for Hydrogen and Natural Gas Storage.” *Energy & Fuels* 31, no. 2, January 2017.
2. M.T. Kapelewski *et al.*, “M<sub>2</sub>(m-dobdc) (M = Mg, Mn, Fe, Co, Ni) Metal–Organic Frameworks Exhibiting Increased Charge Density and Enhanced H<sub>2</sub> Binding at the Open Metal Sites,” *J. Am. Chem. Soc.*, vol. 136, no. 34, pp. 12119–12129, Aug. 2014.
3. Guang Dong Lei, Li Xin Li, Zhi Yun Lu, and Ming Gui Xie, “Improved One-pot Synthesis of 4,6-Dihydroxyisophthalic Acid and 2,3-Dihydroxyterephthalic Acid,” *Chinese Chemical Letters*, vol. 16, no. 8, pp. 1039–1042, 2005.
4. D.J. Sikkema and A.M. Reichwein, “Process for dicarboxylating dihydric phenols,” US6040478, Mar-2000.