IV.A.2 Hydrogen Storage Cost Analysis

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Project End Date: September 29, 2016

Overall Objectives

- Identify and/or update the configuration and performance of a variety of H_2 storage systems for both vehicular and stationary applications.
- Conduct rigorous cost estimates of multiple H_2 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 future pathways to lower system cost.

Fiscal Year (FY) 2013 Objectives

- Update and expand the cost analysis of onboard H_2 storage in pressurized carbon composite (fiber and resin) pressure vessels.
- Validate the cost analysis methodology and results as a function of manufacturing rate against industry estimates, and thereby increase confidence in these estimates.
- Develop a sensitivity analysis of H_2 pressure vessel cost as a function of tank size (4 to 8 kg of H_2/vessel), pressure (350 to 700 bar), and number of pressure vessels within the system (1, 2, or 3).
- Assess the costs of two off-board chemical hydride recycle systems: recycle for the ammonia borane (AB) and alane storage systems.
- Identify cost drivers and future pathways to lower cost.
- Document all analysis results and assumptions.

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_2 storage systems. These values can inform future technical targets for system storage cost.

- Onboard System Hydrogen Storage Cost: \$12/kWh net (2017 target)

FY 2013 Accomplishments

Accomplishments relating to onboard compressed H_2 storage systems:

- Developed pressure vessel system definitions and bills of materials for various tank capacities (4 to 8 kg of H_2/vessel usable H_2) and pressure ratings (350 and 700 bar).
- Worked with Argonne National Laboratory (ANL), the DOE Hydrogen Storage Tech Team, and Ford Motor Company to select tank system specifications for nine configurations (number of tanks, length-to-diameter ratio, geometric parameters, carbon fiber requirements, gravimetric and volumetric capacities, composite efficiency, fiber strength variability, winding efficiency, safety factors, service life, material properties, multi-tank configurations, BOP, etc.) to be used as the basis of comparison with current or projected industry data.
- Worked with ANL to take their ABAQUS model tank results and appropriately include those fiber and resin masses (and dimensions) into the SA Design for Manufacturing and Assembly (DFMA®) cost analysis.
- Updated BOP cost estimates based on original equipment manufacturer (OEM) price quotations and learning curves for production rates outside the quotation range.

- Updated the DFMA cost analysis for five annual production rates, for five tank configurations. Analyzed manufacturing methods. Conducted sensitivity studies.
- Validated key performance parameters for pressure vessels based on discussions with industry, the DOE H2 Storage Tech Team, the Storage System Analysis Working Group, ANL, Pacific Northwest National Laboratory (PNNL), the H2 Storage Engineering Center of Excellence (HSECoE), and project collaborators. Key parameters include (1) the composite fiber and resin masses as a function of tank capacity, (2) fiber and resin material cost, and (3) cost of the BOP components. These are key cost drivers.
- Refined assumptions, models, and analysis based on expert feedback.
- Analyzed the sensitivity of H_2 storage cost to usable H_2 tank capacity (4 to 8 kg H_2), number of tanks (1-3) per system, design pressure (350 and 700 bar), and manufacturing rate (10,000 to 500,000 tank systems/year [sys/yr]).

Accomplishments relating to off-board regeneration of H_2 storage media:

- Completed cost analysis of the off-board regeneration of spent AB (BNH_2) back into an AB (AB or BH_3NH_3) slurry suitable for use in a vehicular onboard H_2 storage system.
- Completed cost analysis of the off-board regeneration of aluminum (spent alane) back into an alane slurry suitable for use in an onboard alane (AlH_3) H_2 storage system.

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INTRODUCTION

The Fuel Cell Technologies Office (FCTO) states that H_2 storage is a key enabling technology for the advancement of H_2 and fuel cell power technologies in transportation, stationary, and portable applications. Consequently, the FCTO has established a goal of developing and demonstrating viable H_2 storage technologies for transportation and stationary applications. This cost assessment project supports the overall FCTO goals by identifying the current technology system components, performance levels, and manufacturing/assembly techniques most likely to lead to the lowest system storage cost. Furthermore, the project is forecasting the cost of these systems at a variety of annual manufacturing rates to allow comparison to the overall 2017 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.

During the second year of the project, onboard H_2 storage in pressurized carbon composite pressure vessels was selected for analysis. While this system has been previously analyzed by DOE, the objective is to update and expand the cost analysis while also validating the cost analysis methodology and results against industry estimates, thereby increasing confidence for future cost analysis projects. Additionally, two off-board chemical hydride recycle systems were selected for cost analysis: recycle for the AB and alane storage systems. The vehicular onboard components of these systems have been previously analyzed. However, an assessment of the off-board recycle costs is needed to allow DOE to assess the full cost of the storage method.

APPROACH

To generate cost estimates for the compressed H_2 pressure vessel system, a DFMA®-style analysis was conducted. Key system design parameters and an engineering system diagram describing process flows were obtained from a combination of industry partners, ANL, and members of the HSECoE [1]. From this system design, the physical embodiment of the system was developed, including materials, scaling, dimensions, and design. Based on this physical embodiment, the manufacturing process train was modeled to attain the cost to manufacture each part. Industry partners were consulted to assess current and future manufacturing procedures and parameters. Cost was based on the capital cost of the manufacturing equipment, machine rate of the equipment, equipment tooling amortization, part material costs, and other financial assumptions. Once the cost model was complete for the system design, sensitivity data for the modeled technology was obtained by varying the key parameters. These results were shared with ANL, the National Renewable Energy Laboratory (NREL), 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 OEM price are explicitly not included in the modeling. These costs are excluded from this analysis: profit and markup; one-time costs such as non-recurring research/design/engineering; and general expenses such as general and administrative costs, warranties, advertising, and sales taxes.

The off-board regeneration cost analysis for the alane and AB systems is based on a less-detailed cost analysis methodology. For each of the systems, a process flow diagram is developed based on input from ANL. The AB regeneration system is based on the Los Alamos National Laboratory (LANL) one-pot process using hydrazine (N_2H_4) to recycle spent AB (BNH_2) back into AB (BH_3NH_3) [2-4]. Since hydrazine is a major cost contributor in the regeneration process, hydrazine cost is independently analyzed based on the benzophenone process, which converts ammonia, oxygen, and water into hydrazine [5]. The alane regeneration system is based on the dimethylethylamine (DMEA) process [6]. Both regeneration systems are nominally sized for a central plant with an equivalent capacity of 100 metric tons per day of H_2. A modified form of the H2A H_2 production cost analysis spreadsheet [7] is used to assess regeneration cost. While we do not seek to compute H_2 production costs, the H2A model is based on a discounted cash flow tool that applies to this regeneration analysis. Furthermore, the H2A model is a transparent and familiar tool to the H_2 community. Regeneration costs are computed per kg of H_2 eventually releasable onboard the vehicle. Capital costs of the systems are estimated by a summation of major subsystems identified on the process flow diagram, and are based on handbook [8] capital cost correlations for the type of subsystem and pertinent scaling factors (such as flow rate, pressure, temperature, etc.).

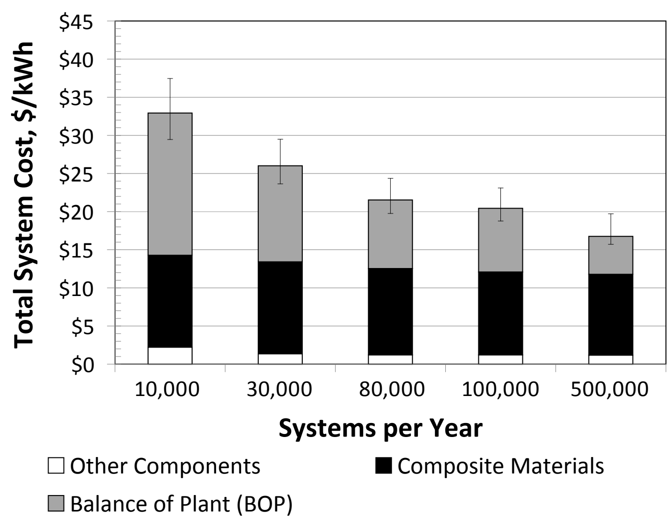
RESULTS

The results from sensitivity studies on compressed H_2 pressure vessel storage systems demonstrate the effects of varying tank design parameters and annual production rates. Figure 1 shows the cost breakdown for single-tank H_2 storage systems holding 5.6 kg of usable H_2 and operating at up to 70 Megapascals (MPa) (i.e., 700 bar), as a function of manufacturing rate. H_2 storage costs range from ~\$33/kWh (at 10,000 sys/year) to ~\$17/kWh (at 500,000 sys/year). Projected costs are based on year 2007 U.S. dollars with H_2 energy based on the lower heating value (33.3 kWh/kgH_2). Error bars represent plus and minus two standard deviations (middle 95.4% of expected costs assuming a normal distribution). The H_2 storage cost per unit energy decreases significantly with increased annual production rate. Results indicate that the two most significant cost drivers are (1) the composite materials costs (primarily the carbon fiber cost) and (2) the cost of BOP components. Further analyses show that these remain the two key cost drivers for the range of operating pressures, tank configurations, and manufacturing rates evaluated in this project so far. BOP components are revised from previous analyses and incorporate recommendations from industry for enhanced functionality and safety.

As shown in Figure 1, the materials costs decline only moderately with manufacturing rate (~12% over a production increase from 10,000 to 500,000 sys/yr) while the BOP cost declines significantly (~73%) over the same range. BOP costs scale down significantly in moving to higher annual production volumes due to both manufacturing economies of scale and projected design improvements made economical by high production. As a result, the composite materials costs become a higher percentage of total system costs in moving to higher annual production volumes.

Figure 2 shows the cost breakdown for dual-tank H_2 storage systems holding 5.6 kg of usable H_2 and operating at up to 35 MPa (i.e., 350 bar), as a function of manufacturing rate. In contrast to Figure 1, at all but the highest production levels, the key cost driver is the BOP. BOP costs are greatly impacted by economies of scale in mass production, whereas composite materials costs benefit less so. As shown in the figure, the materials costs decline only moderately with manufacturing rate (~12% over a production increase from 10,000 to 500,000 sys/year) while the BOP cost declines significantly (~74%) over the same range. H_2 storage costs range from ~\$37/kWh (at 10,000 sys/year) to ~\$15/kWh (at 500,000 sys/year).

Based on techno-economic modeling of the LANL one-pot, hydrazine-based, AB recycle system, the AB regeneration cost is estimated at about \$10 per kg of H_2 releasable on the vehicle, even assuming a future hydrazine market price of \$1/kg N_2H_4. This is a prohibitively high cost and suggests that alternative AB regeneration routes may be more promising. A sensitivity analysis indicates that the AB regeneration cost is highly sensitive to hydrazine price, which, in turn, is most sensitive to 1) ammonia costs and 2) hydrazine plant capital costs. Hypothetically speaking, if the hydrazine cost were zero, the AB regeneration cost would be about \$2.28/kg H_2, which is still higher than the competitive H_2 target of \$2/kg H_2. Thus, according to this analysis, it appears quite financially challenging to try



Other Components Include:	
System Assembly	B-Stage Cure (Cure #1)
He Fill and Leak Test	Fiber Winding
HydroTest	Linear Annealing
Boss (Materials and Processing)	Linear Formation (Materials and Processing)
Full Cure (Cure #2)	

FIGURE 1. System Cost Results for Compressed H_2 Storage: 70 MPa, Single Tank, 5.6 kg H_2 Usable Capacity

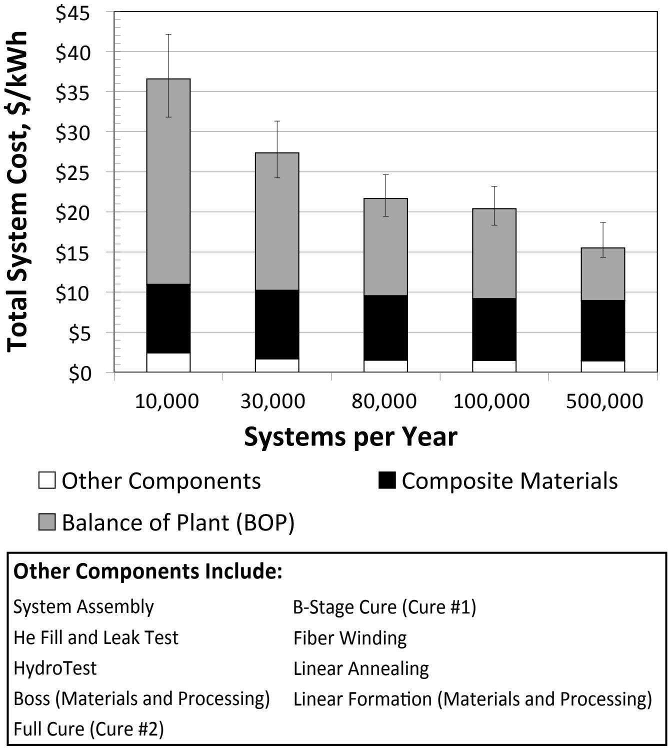


FIGURE 2. System Cost Results for Compressed H_2 Storage: 35 MPa, Dual Tank, 5.6 kg H_2 Usable Capacity

to regenerate spent AB based on the hydrazine method. Preliminary results from the alane regeneration process (DMEA pathway) indicate that this approach may be more cost competitive than the AB regeneration process, although still expensive. The alane off-board regeneration cost is estimated at \$4/kg H_2. At the same time, capital cost estimates for the AB and alane off-board regeneration processes are uncertain due to a lack of optimized process conditions, particularly reactor residence times.

Figure 3 shows that the off-board regeneration cost for either AB or alane is a significant cost driver to the overall well-to-wheel (WTW) cost of H_2 delivered to the vehicle. The off-board regeneration cost makes the WTW costs of both AB and alane scenarios more expensive than either compressed gas or liquid H_2 scenarios. Figure 4 shows similar results, but for energy use. The off-board regeneration energy consumption for either AB or alane is a significant contributor to the overall WTW energy consumption of H_2 delivered to the vehicle. The off-board regeneration energy consumption makes the WTW energy consumption of both AB and alane scenarios less efficient than either compressed gas or liquid H_2 scenarios.

CONCLUSIONS AND FUTURE DIRECTIONS

Based upon work from this year, the following conclusions and future directions are revealed:

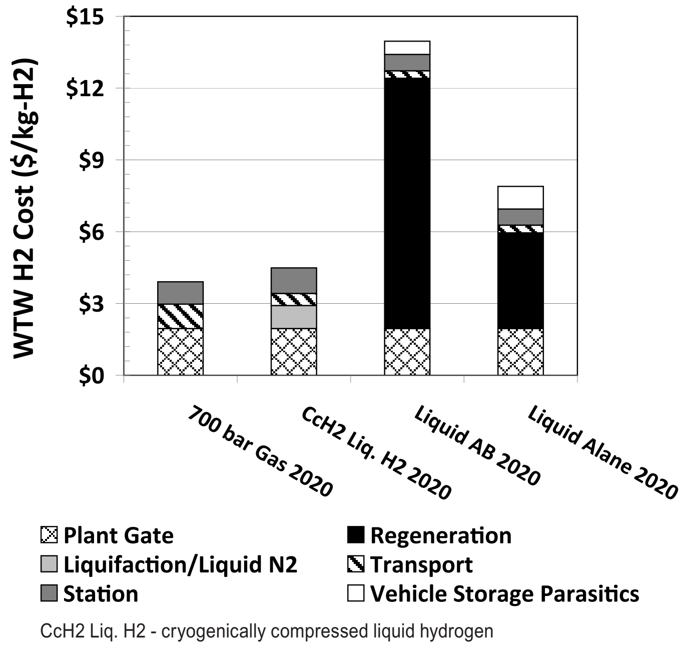


FIGURE 3. Well-to-wheel (WTW) Cost of H_2 Delivered to the Vehicle

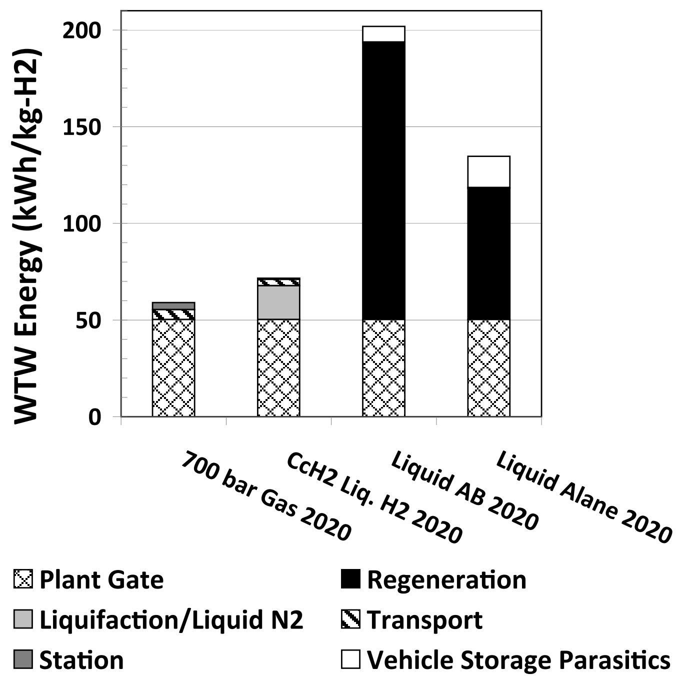


FIGURE 4. WTW Energy Consumption for H_2 Delivered to the Vehicle

- Key cost drivers for carbon fiber pressure vessel systems are (1) the carbon fiber materials cost and (2) the BOP component costs. Thus, accurate estimation of the carbon fiber price and the mass of fiber required in each vessel is very important, as are efforts to simplify and reduce the size and extent of the BOP.

Costs for compressed H_2 storage systems holding 5.6 kg H_2 usable are estimated at:

- Single-tank system at 700 bar:
  - ~$33/kWh at 10,000 systems/year
  - ~$17/kWh at 500,000 systems/year
- Single-tank system at 350 bar:
  - ~$29/kWh at 10,000 systems/year
  - ~$13/kWh at 500,000 systems/year
- Dual-tank system at 700 bar:
  - ~$40/kWh at 10,000 systems/year
  - ~$19/kWh at 500,000 systems/year
- Dual-tank system at 350 bar:
  - ~$37/kWh at 10,000 systems/year
  - ~$15/kWh at 500,000 systems/year
- The AB (hydrazine regeneration pathway) and alane (DMEA regeneration pathway) off-board regeneration costs are estimated at ~$10/kg H_2 and $4/kg H_2, respectively. These costs are prohibitively high and result in life cycle costs two to four times higher than compressed or liquefied H_2 life cycle costs. Other regeneration pathways may result in lower cost.

Future work will:

- Continue to refine the H_2 pressure vessel cost analysis.
- Gather further OEM data on BOP component costs.
- Explore BOP component simplification and combined functionality as a pathway to lower cost.
- Redesign and re-cost the tank mounting mechanisms from complex frame-mounted systems to less equipment-intensive approaches.
- Assess the cost impact of advanced tankage concepts such as use of strength-graded fibers, carbon nanotube addition between fiber layers to increase translational strength, and cold H_2 storage (200 Kelvin).

FY 2013 PUBLICATIONS/PRESENTATIONS

1. James, B.D., Spisak, A.B., Colella, W.G., *Hydrogen Storage Cost Analysis,* annual report for the U.S. DOE EERE FCT program, July 2012.

2. James, B.D., Colella, W.G*., Alane and Ammonia Borane Off-Board Recycle Analysis Status,* presentation to U.S. DOE EERE FCT Headquarters, Forrestal Building, Washington, D.C., Sept. 25th, 2012.

3. James, B.D., Colella, W.G*., Analysis of Recycling Alane and Ammonia Borane Off-Board Vehicles,* presentation to U.S. DOE Hydrogen Storage Engineering Center of Excellence, delivered remotely, Arlington, VA, Oct. 11th, 2012.

4. James, B.D., Colella, W.G., Paster, M., *Energy, Emissions, and Economic Analysis of Off-board Recycling of Alane and Ammonia Borane for Hydrogen Fuel Cell Vehicles,* presentation to U.S. DOE EERE Fuel Pathway Integration Technical Team (FPITT), delivered remotely, Arlington, VA, Oct. 24th, 2012.

5. James, B.D., Spisak, A.B., *Pressure Vessel Cost Analysis*, presentation to Storage Systems Analysis Working Group (SSAWG) & H2 Storage Tech Team, delivered remotely, Arlington, VA, Nov. 14th, 2012.

6. James, B.D., Spisak, A.B., *Pressure Vessel Cost Analysis*, presentation to DOE Storage Principal Investigator Meeting, Washington, DC (ARPA-E offices), Nov. 28th, 2012.

7. James, B.D., Moton, J.M., "Updated Pressure Vessel Balance of Plant and System Costs," update to DOE Storage Team, Arlington, VA, March 12th, 2013.

8. Colella, W.G., "Advanced Electrochemical Systems," *California Renewable Energy and Storage Technology Conference*, California State University Northridge, Northridge, CA, May 4th, 2013.

9. James, B.D., Moton, J.M., Colella, W.G., "Hydrogen Storage Cost Analysis, Preliminary Results," presentation at the 2012 DOE Hydrogen and Fuel Cells Program Review, Arlington, VA, May 15th, 2013.

10. James, B.D., Moton, J.M., Colella, W.G., "Advanced Hydrogen Compression Systems for Serving a Hydrogen Vehicle Refueling Infrastructure," *American Society of Mechanical Engineers (ASME) 2013 7th International Conference on Energy Sustainability*, Minneapolis, MN, July 14–19th, 2013 (in preparation).

11. James, B.D., Colella, W.G., Moton, J.M., *Hydrogen Storage Cost Analysis*, annual report for the U.S. DOE EERE FCT program, July 2013.

REFERENCES

1. "Technical assessment of compressed hydrogen storage tank systems for automotive applications," T.Q. Hua, R.K. Ahluwalia, J.-K. Peng, M. Kromer, S. Lasher, K. McKenney, K. Law, J. Sinha, International Journal of Hydrogen Energy 36 (2011) 3037-3049. (doi:10.1016/j.ijhydene.2010.11.090)

2. Sutton, A.D., "Efficient Regeneration of Ammonia Borane," ACS Meeting, Aug. 20, 2009.

3. Sutton et al., "Regeneration of Ammonia Borane Polyborazylene," U.S. Patent Application 2010/0272622 A1, October 28, 2010.

4. "Off-board Regeneration of Ammonia Borane for Use as a Hydrogen Carrier for Automotive Fuel Cells," Thanh Hua, Rajesh Ahluwalia, submission for publication in the International Journal of Hydrogen Energy, April 2, 2012.

5. "Hydrazine Production from Ammonia via Azine," Hiromu Hayashi et. al., Industrial and Engineering Chemistry Product Research and Development, Vol. 15 No. 4 (1976) 299-303.

6. "Alane hydrogen storage for automotive fuel cells - Off-board regeneration processes and efficiencies," Thanh Q. Hua, Rajesh K. Ahluwalia, International Journal of Hydrogen Energy, Volume 36, Issue 23, November 2011, Pages 15259–15265. (doi:10.1016/j.ijhydene.2011.08.081)

7. "H2A Hydrogen Production Analysis Model Version 3," Darlene Steward, National Renewable Energy Laboratory, presented at 2012 DOE Hydrogen and Fuel Cells Program Review, Washington, DC, May 15, 2012.

8. Peters, Max S., Timmerhaus, Klaus D., West, Ronald E., Equipment Costs Plant Design and Economics for Chemical Engineers – 5th Edition, (New York, NY: McGraw-Hill, 2002). http://www.mhhe.com/engcs/chemical/peters/data/ce.html

9. "Low-Cost Precursors to Novel Hydrogen Storage Materials," Final Report, Suzanne W. Linehan, Arthur A. Chin, Nathan T. Allen, Robert Butterick, Nathan T. Kendall, I. Leo Klawiter, Francis J. Lipiecki, Dean M. Millar, David C. Molzahn, Samuel J. November, Puja Jain, Sara Nadeau, Scott Mancroni, The Dow Chemical Company, December 31, 2010, Prepared for U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy Hydrogen Program, Hydrogen Storage, Under Contract DE-FC36-05GO15053.