

IV.E.3 Cost Analyses of Hydrogen Storage Materials and On-Board Systems

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Contract Number: DE-FC36-04GO14283

Start Date: June 2004

Projected End Date: March 2012

Fiscal Year (FY) 2011 Objectives

The overall objective for this project is provide independent analysis to help guide the DOE and developers toward promising research and development (R&D) and commercialization pathways by evaluating the various on-board hydrogen storage technologies on a consistent basis. Specific objectives include:

- Compare different on-board hydrogen storage approaches in terms of lifecycle costs, energy efficiency and environmental impact;
- Identify and compare other performance aspects that could result in barriers to successful commercialization (e.g., on-board system weight and volume);
- Examine the effects of system-level cost and performance trade-offs for different storage approaches; and
- Project performance and cost relative to DOE targets.

Technical Barriers

This project addresses the following technical barriers from the Hydrogen Storage section of the Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-Year Research, Development, and Demonstration Plan:

- (A) System Weight and Volume
- (B) System Cost
- (K) System Life-Cycle Assessments

Technical Targets

This project evaluates the various on-board hydrogen storage technologies being developed by the DOE Hydrogen Storage Centers of Excellence and independent projects. Insights gained from these evaluations will help guide DOE and developers toward promising hydrogen storage materials and system-level designs and approaches that could meet the DOE targets for storage system cost, specific energy, energy density, fuel cost, and efficiency.

FY 2011 Accomplishments

We have performed preliminary and/or updated assessments for several hydrogen storage systems. For each system assessment, we projected on-board system performance and high-volume (~500,000 units/year) manufactured cost, as well as determined the critical cost drivers and conducted single- and multi-variable sensitivity analyses to bound cost results. We have also completed a preliminary analysis of low-volume compressed single-tank systems. We also reviewed key assumptions and results with developers, DOE, and stakeholders (e.g., material suppliers, national labs, FreedomCAR and Fuel Partnership Tech Teams) and incorporated their feedback into the final results. Finally we compared performance and cost results to other baseline technologies and DOE targets for the on-board storage system. Specific accomplishments include:

- Completed preliminary low-volume (10,000, 30,000, 80,000, 130,000, and 500,000 units/year) on-board system factory cost assessments for 350 and 700 bar compressed single-tank systems. The projected costs for the 350 bar system are \$29, \$26, \$20, \$18, and \$15/kWh for 10,000, 30,000, 80,000, 130,000, and 500,000 units per year, respectively. The projected costs for the 700 bar system are \$36, \$33, \$25, \$22, and \$19/kWh for 10,000, 30,000, 80,000, 130,000, and 500,000 units per year, respectively.
- Completed a review of Dow Chemical's ammonia borane (AB) off-board first fill and fuel regeneration cost projections and submitted a final memo to DOE summarizing these results.
- Finalized the liquid carrier hydrogen (LCH₂) storage system cost analysis, submitted a final report to DOE for review, and submitted an executive summary to Argonne National Laboratory (ANL) for inclusion in the combined ANL/TIAX final report. Compared to TIAX's prior analysis, the updated LCH₂ storage system uses an updated catalyst replacement rate, adjusted material and balance-of-plant (BOP) costs, and several additional minor changes. These changes reduced the cost of hydrogen fuel by over 30% from \$4.75 to \$3.27 and increased the cost of onboard storage by less than 5%, from \$15.4 to \$15.7/kWh.

- Reviewed and completed analysis for metal organic framework (MOF)-177 and AX-21. We developed a bottom-up cost estimate for MOF-177 and continued to use an older estimate for AX-21. Reviewers felt the approach used for MOF was generally sound, though characterized by high uncertainty. The AX-21 cost estimate is based on information from the literature, and may be high. Rather than revisit the AX-21 cost, we expanded our sensitivity analysis to capture this uncertainty.
- Revised and completed high-volume on-board system factory cost assessments of cryo-compressed and 350 bar and 700 bar compressed tank systems. For the compressed systems, the analysis was extended to include Type 3 and Type 4 tanks and single and dual tank systems. We submitted a revised final report to DOE for review and submitted a revised executive summary to ANL for inclusion in the combined ANL/TIAX final report.
- Supported the Storage Systems Analysis Working Group (SSAWG) evaluation of the well-to-tank (WTT) energy use and greenhouse gas emissions for MOF-177 tanks, cryo-compressed tanks, 350 and 700 bar tanks, and cold gas tanks.



Introduction

DOE is funding the development of a number of hydrogen storage technologies as part of its “Grand Challenge” applied R&D program. This independent analysis project helps guide the DOE and Grand Challenge participants toward promising R&D and commercialization pathways by evaluating the various hydrogen storage technologies on a consistent basis. Using this consistent and complete comparison of various technology options, R&D can be focused and accelerated. Without such an approach, erroneous investment and commercialization decisions could be made, resulting in wasted effort and risk to the development of hydrogen vehicles and a hydrogen infrastructure.

TIAX is conducting system-level evaluations of the on-board storage systems cost and performance for four broad categories of on-board hydrogen storage. The four categories are: reversible on-board (e.g., metal hydrides and alanates), regenerable off-board (e.g., chemical hydrides); and high surface area sorbents (e.g., carbon-based materials), and advanced physical storage (e.g., cryo-compressed hydrogen, liquid hydrogen). Evaluations are based on developers’ on-going research, input from DOE and key stakeholders, and in-house expertise.

Approach

This project utilizes an approach that is designed to minimize the risks associated with achieving the project

objectives. In coordination with ANL, system-level conceptual designs are developed for each on-board storage system and required fueling infrastructure. We work closely with ANL to develop a bill of materials consistent with their performance assessment. Next, system models and cost models are used to develop preliminary performance and cost results. We utilize in-house activities and product-based cost models to determine high-volume manufactured cost projections for the on-board storage system, and H₂A-based discounted cash flow models to estimate hydrogen selling prices based on the required off-board hydrogen infrastructure. Subsequently, these results are vetted with developers and key stakeholders and refined based on their feedback. Coordination with DOE’s Hydrogen SSAWG avoids duplication and ensures consistency. This is an on-going and iterative process so that DOE and its contractors can increasingly focus their efforts on the most promising storage technology options.

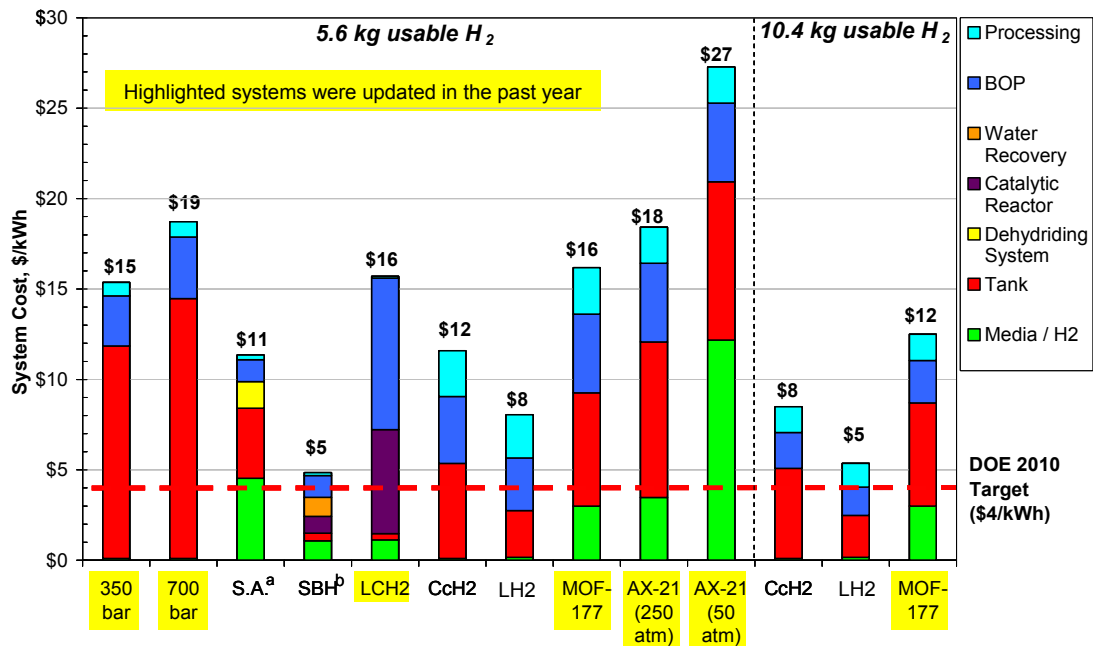
Results

TIAX developed preliminary cost estimates for low-volume manufacturing of 350 and 700 bar compressed storage systems, and updated and completed previous cost estimates for compressed (high-volume one and two tank), cryo-compressed, MOF-177, AX-21, ammonium borane, and LCH₂ storage systems. Each of the storage system cost projections are estimated based on on-board system designs developed by ANL [1]. Figure 1 shows the updated costs for the systems completed in FY 2011. The remaining portion this section discusses the preliminary low-volume manufacturing cost analysis for compressed systems.

Low-volume manufacturing costs were estimated for 10,000, 30,000, 80,000, 130,000, and 500,000 units per year for both 350 and 700 bar systems. The preliminary cost estimate focused mainly on the cost of carbon fiber, differences in manufacturing costs, and BOP costs. The systems modeled are identical to those used for the cost estimate for the 500,000 units per year shown in Figure 1. Figure 2 shows the preliminary costing results for low-volume manufacturing of compressed systems.

The carbon fiber cost for low- and high-volume manufacturing, based on conversations with carbon fiber manufacturers, will stay relatively the same with potentially a small price decrease of \$1.5/lb around 80,000 units per year. The projections of carbon fiber cost may go up, independent of volume, due to increases in the costs of carbon fiber precursors. Figure 2 shows that tank material costs, which do not include manufacturing and are primarily carbon fiber costs, remain relatively constant, due to carbon fiber costs remaining relatively constant.

Manufacturing costs were projected assuming a high level of automation, similar to that of high-volume manufacturing. This assumption was made based on the significant amount of manufacturing still required for 10,000 units per year. After recent discussions with tank manufacturers, this assumption will be the main revision for



^a The sodium alanate system requires high temp. waste heat for hydrogen desorption, otherwise the usable hydrogen capacity would be reduced.
^b SBH = Sodium borohydride, "A NO-GO decision was made on the hydrolysis of SBH for on-board application"

FIGURE 1. Updated Hydrogen Storage System Costs

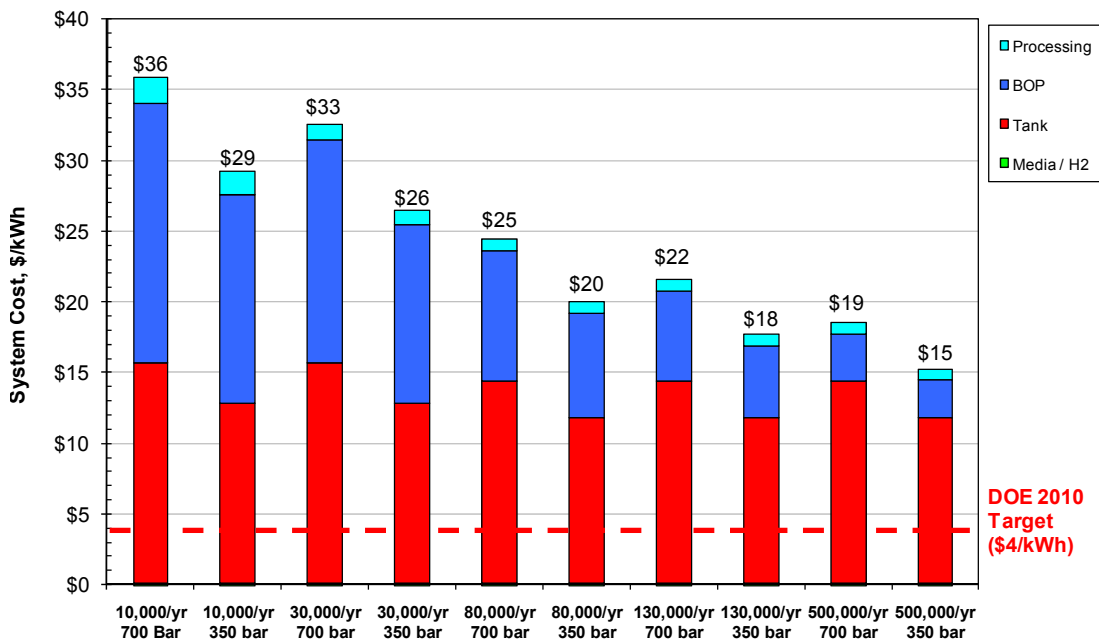


FIGURE 2. Preliminary Low-Volume Manufacturing Results for One-Tank 350 and 700 Bar Compressed Systems

the finalized of cost estimates for low-volume manufacturing. Figure 2 shows that with the assumption of a high level of automation, processing costs are very small compared to tank and BOP costs.

The cost that is most affected by manufacturing volume is the BOP cost. This is a result of components, especially

valves, regulators, and sensors, being made at low volumes at the specifications required for high pressure hydrogen. Many of these components need to be individually machined, which is more costly than being forged. The basis of the cost curve for the BOP components is data supplied by a sensor manufacturer and their projected costs for 10,000, 100,000, and 500,000 units per year.

The projected costs for the 350 bar system are \$29, \$26, \$20, \$18, and \$15/kWh for 10,000, 30,000, 80,000, 130,000, and 500,000 units per year, respectively. The projected costs for the 700 bar system are \$36, \$33, \$25, \$22, and \$19/kWh for 10,000, 30,000, 80,000, 130,000, and 500,000 units per year, respectively. The BOP components decreased from 50% of the total cost at 10,000 units per year to 17% at 500,000 units per year. The tank increased from 44% of the total cost at 10,000 units per year to 78% at 500,000 units per year.

Conclusions and Future Directions

The cost assessments conducted this year allow direct comparison with prior cost assessments and DOE targets. Our models allow us to identify critical cost components, which enables focused discussion with tank developers and manufacturers.

- None of the systems assessed meet DOE's 2010 cost target of \$4/Wh. The cost of the 5.6 kg 350 bar, 700 bar, cryo-compressed, liquid, and MOF-177 storage systems range from 2 to 5 times the cost of the DOE target. Key factors influencing system costs are the carbon fiber material cost, the cost of aluminum, and in the case of the MOF system, the storage media.
- The low-volume compressed systems are 7 and 9 times the 2010 DOE target of \$4/kWh, with the cost of BOP components showing the greatest potential for cost reduction.
- The MOF-177 system cost is 3 and 4 times the 2010 DOE target of \$4/kWh for the 10.4 and 5.6 kg systems, respectively. Achieving the DOE cost targets will require large reductions in the cost of the storage media and the tank materials (aluminum and carbon fiber).
- The onboard liquid hydrogen system cost is 1.3 and 2 times the 2010 DOE target for the 10.4 and 5.6 kg systems, respectively. While the liquid system has amongst the lowest onboard storage system cost, it has low volumetric efficiency, WTT efficiency, and high fuel costs. These shortcomings are a function of fuel boil off and the high energy requirement associated with liquefaction.
- The cryo-compressed system is 2 and 3 times the 2010 DOE target for the 10.4 and 5.6 kg systems, but meets the 2010 volumetric and gravimetric targets. The base case 350 bar and 700 bar systems are 4 and 5 times higher than the 2010 DOE targets for the 350 bar Type 4 and 700 bar Type 4 systems, respectively, and both systems fall short of the 2010 volumetric capacity targets. Additional analysis of 350 and 700 bar dual tank systems showed minor cost increases of less than 5%; 350 and 700 bar Type 3 systems showed moderate cost increases on the order of 10%. The major cost driver for the compressed system is carbon fiber, while the cryo-compressed system cost is driven by carbon fiber, aluminum liner, and BOP component costs.

The rest of this fiscal year, we plan to continue to work with developers and stakeholders to improve the accuracy of the analyzed on-board and off-board system models and finalize our analysis of storage technology options. Specifically, we plan to:

- Refine the modeling and analysis and complete the report for the low-volume manufacturing of 350 and 700 compressed systems.
- Perform the preliminary and final costing analysis of the MOF-5 system.
- Continue to work with DOE, SSAWG, Centers of Excellence, other analysis projects, developers, Tech Teams and other stakeholders (as necessary) to revise and improve system models.

FY 2011 Publications/Presentations

1. Kromer, M. *et al.* "Review of Cost Assessment for Ammonia Borane 1st Fill and Regeneration Process." TIAX LLC. Memo to Dow Chemical and the Department of Energy. August 25, 2010.
2. Kromer, M. *et al.* "H₂ Storage using Compressed Gas: On-board System and Ownership Cost Update for 350 and 700-bar." TIAX LLC. Final Report to the Department of Energy. August 27, 2010.
3. Kromer, M. *et al.* "H₂ Storage using a Liquid Carrier: Off-board and On-board System Cost Assessments." TIAX LLC. Final Report to the Department of Energy. September 14, 2010.
4. Kromer, M. *et al.* "Project Overview and Status Update." TIAX LLC. Presentation to the Department of Energy. November 9, 2010.
5. Kromer, M. *et al.* "H₂ Storage using Carbon Sorbents: On-board System Cost Assessment." TIAX LLC. Final Report to the Department of Energy. December 13, 2010.
6. Kromer, M. *et al.* "Overview of Approach and FY 2011 Activities." TIAX LLC. Presentation to Hydrogen Storage Systems Analysis Working Group. January 12, 2011.
7. Law, K. *et al.* "Analyses of Compressed Hydrogen On-Board Storage Systems." TIAX LLC. Presentation to Compressed and Cryo-Compressed Hydrogen Storage Workshop. February 14, 2011.
8. Law, K. *et al.* "Updated Hydrogen Storage System Cost Assessments." TIAX LLC. Presentation to DOE Hydrogen Storage Tech Team. April 28, 2011.
9. Law, K. *et al.* "Updated Hydrogen Storage System Cost Assessments." TIAX LLC. Presentation at DOE Annual Hydrogen Merit Review. May 11, 2010.

References

1. Ahluwalia, R.K., Hua, T.Q., Peng, J.K. "System Level Analysis of Hydrogen Storage Options." 2010 DOE Hydrogen Program Review, June 7–11, 2010.