# II.A.1 Analysis of Advanced $H_2$ Production Pathways

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Project End Date: September 30, 2020

## Overall Objectives

- Perform cost analysis of various hydrogen ($H_2$) production and delivery pathways.
- Identify key cost and performance bottlenecks of the given pathways.
- Conduct deep dive analyses and optimization studies on hydrogen delivery scenarios.
- Supply information from techno-economic studies to the U.S. Department of Energy (DOE) for life cycle analysis.
- Respond to the scope and topic areas as defined by the DOE.

## Fiscal Year (FY) 2017 Objectives

- Identify a methodology for the evaluation of Hydrogen Analysis (H2A) model cases with low technology readiness level (TRL).
- Conduct a techno-economic analysis on a cascade storage pressure vessel designed by WireTough Cylinders LLC.

## Technical Barriers

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

(E) Gaseous Hydrogen Storage and Tube Trailer Delivery Costs

## Technical Targets

*Techno-economic analysis of a cascade storage system:* The goal of this project is to conduct techno-economic analyses of DOE-supported hydrogen production and delivery projects in an effort to identify key cost drivers and process bottlenecks. Currently, the analysis work is focused on advanced designs for a steel-wire-overwrapped, Type II stationary hydrogen storage system that may lead to significantly reduced dispensing site hydrogen storage costs compared to the FY 2015 cost of high pressure cascade storage of \$2,000/kg $H_2$ uninstalled.

## FY 2017 Accomplishments

- Developed a methodology for analyzing H2A case studies with low-TRL, emerging technologies while obtaining high-confidence cost prediction results.
- Completed a preliminary techno-economic analysis for a wire-wrapped steel vessel suitable for high pressure cascade storage of $H_2$.

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## INTRODUCTION

Year 1 activities consist of two main tasks. The first task of the project was to develop a cost analysis methodology capable of providing high confidence in the accuracy of results for low-TRL H2A case studies.[1] In previous analyses, cases based on high-TRL technologies were validated by comparing modeling results with actual cost and technical assumptions from commercial units. However, with low-TRL technologies, the emerging technology being analyzed does not have a commercial product against which to compare the case study projections. As such, a "low-TRL methodology" was devised that would help to ensure accurate results for H2A cases centered on emerging technologies.

The second Year 1 task of the project is to conduct H2A or techno-economic analyses that are assigned by DOE. DOE selected a project for stationary high pressure cascade storage of $H_2$ at forecourt dispensing stations. The storage technology consists of a Type II steel-wire-wrapped pressure vessel that avoids use of high-cost carbon composites, as is often used in high pressure storage. A full Design for Manufacture and Assembly (DFMA®) cost analysis was used to model the wire-wrapped vessel manufacturing process. Further, the

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[1] H2A is a discounted cash flow model that is used to predict the cost of production and delivery of hydrogen for a given process.

analysis was extended to incorporate the balance of system components of the full cascade storage system to identify a cost suitable for a hypothetical refueling station with the capability of refueling six vehicles simultaneously. These results may be incorporated into a full H2A cost analysis of the dispensing station and other distribution models.

## APPROACH

In order to develop the low-TRL methodology, the validated process for high-TRL case studies was modified. The methodology was then reviewed by all members of the project team and submitted to DOE for review.

In order to properly analyze the hydrogen storage vessel developed by WireTough Cylinders LLC, a ground-up (DFMA®) approach was used. The DFMA® process breaks down each manufacturing process step into a material cost, a labor cost, and a utility cost. The capital cost of the equipment is amortized over the life of the equipment and combined with the material, labor, and utility costs; then, a manufacturing cost is obtained. Key process parameter values for the DFMA® analysis were provided by WireTough. These parameters were further supported by material and equipment cost quotations from various manufacturers. All process parameters and assumptions were reviewed by WireTough for accuracy and appropriateness.

## RESULTS

The newly developed low-TRL methodology is comprised of four main steps. In the first step, information is gathered from a technology transfer from the product developer, extensive literature searches, and examination of similar technologies. In the second step, a system design is developed. The team determines if single design or multiple system design variants are required. The system(s) are designed, and all relevant parameters are identified. In the third step, the selected system designs are thoroughly reviewed before utilizing the system design for H2A case studies. All relevant input parameters are combined with the system design to create an H2A case. The H2A case is also run through a Monte Carlo stochastic analysis to determine the most likely hydrogen production cost given uncertainty in the input parameters. As a final step, the process is reviewed, documented, and published. Figure 1 graphically represents each step of the low-TRL H2A case study cost analysis methodology.

After the updated methodology for TRL identification was completed, DOE requested a cost analysis of WireTough's process to create Type II steel-wire-wrapped pressure vessels. The complete vessel fabrication process is illustrated in Figure 2. The wire-wrapping process begins with a 30 foot long steel liner rated for approximately 6,600 psi.[2] The liner is carried by crane to a wire-wrapping station, which combines 24 steel wires into a wire tow band

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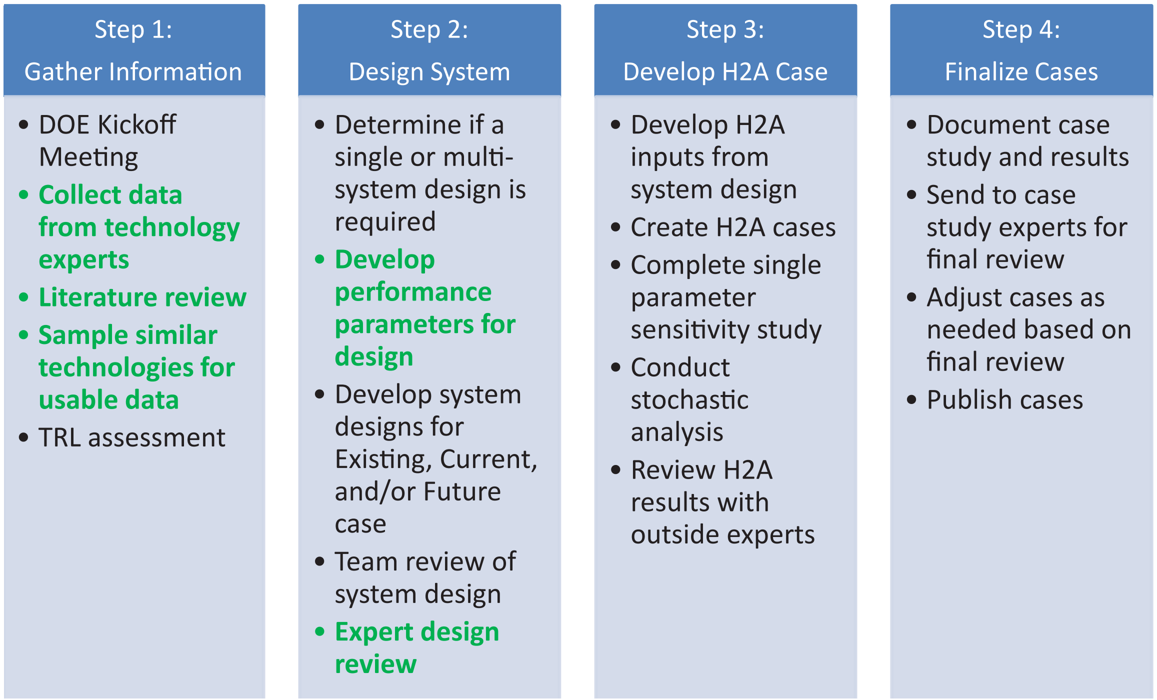
[2] For clarity within this report, the solid-metal walled pressure vessel is called a liner, while the completed, wire-wrapped product is termed a pressure vessel.



Step 1:
Gather Information

- DOE Kickoff Meeting
- **Collect data from technology experts**
- **Literature review**
- **Sample similar technologies for usable data**
- TRL assessment

Step 2:
Design System

- Determine if a single or multi-system design is required
- **Develop performance parameters for design**
- Develop system designs for Existing, Current, and/or Future case
- Team review of system design
- **Expert design review**

Step 3:
Develop H2A Case

- Develop H2A inputs from system design
- Create H2A cases
- Complete single parameter sensitivity study
- Conduct stochastic analysis
- Review H2A results with outside experts

Step 4:
Finalize Cases

- Document case study and results
- Send to case study experts for final review
- Adjust cases as needed based on final review
- Publish cases

**FIGURE 1.** Low-TRL H2A process workflow. Steps in green are conducted for low-TRL cases but not high-TRL cases. All other steps are conducted in both high- and low-TRL cases.

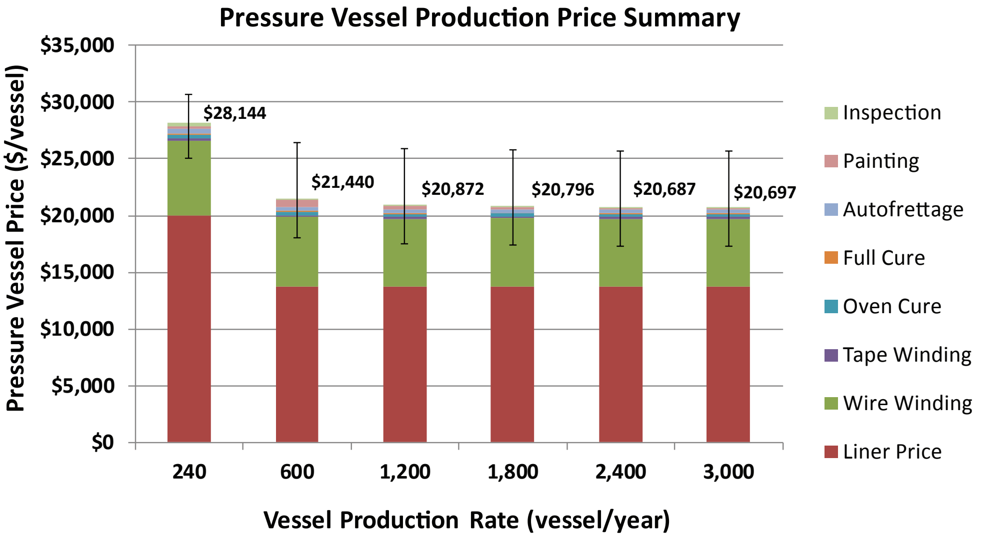


**FIGURE 2.** Process flow diagram for creating a wire-wound pressure vessel rated for over 1,000 bar (13,000 psi)

and then wraps the wire tow band around the cylindrical section of the liner. As the wires are wrapped around the liner, epoxy is applied to the wires. As understood, the purpose of the epoxy is to protect the wires from corrosion, provide added strength/rigidity, and prevent wire movement. Finally, the outer layer of wires is taped with non-adhesive dry wall tape and then covered with epoxy. The end-domes of the liner are not covered in the wire-wrapping process. After wrapping the liner with wire, the assembly is sent to an oven for partial epoxy curing and is then cured at room temperature to complete the process. The pressure vessel is then put through an autofrettage process. Finally, the pressure vessel is painted with an ultraviolet-resistant paint.

The projected price (after markup)[3] of the complete pressure vessel at low production volumes, as it is currently manufactured, is approximately $28,266/unit (based on a one-vessel-per-day production rate). At higher production rates and with process adjustments to account for automation, the projected price drops to under $21,000/unit. The limited variation in costs at production rates between 240 and 3,000 pressure vessels per year is a result of a constant liner cost being used at each of those production rates. With such a dominant cost being held constant at different production rates, the variation in total cost with varying production rate is minimized. When compared to DOE storage cost targets, the wire-wrapped vessels show significant improvement over the FY 2015 cost status and nearly reach the FY 2020 cost target of $600/kg (see Figure 3).[4]

The analysis was extended to develop a suitable storage cost for use in H2A cases. In order to do this, a theoretical balance of system was developed to formulate a cost for a storage system that could be used at a hydrogen forecourt station. The theoretical station would have a bank of three sets of two tanks and feed to six dispensers. When possible, the components required for the balance of system (valves, pressure relief devices, thermocouples, etc.) were quoted by various manufacturing companies. When price quotes were not available, Systems Analysis used historical data to generate prices for components. The balance of system also includes projected costs for installation, mark-up, and component assembly and testing. The combination of the storage vessel prices and the balance of system prices can then be used as a total system cost for analysis of the delivered price of hydrogen. This cost is readily used in H2A, and it may be worth updating H2A with the results of this analysis.

## CONCLUSIONS AND UPCOMING ACTIVITIES

The above described methodology for analyzing low-TRL H2A cases provides a framework for developing reliable results. The new methodology is expected to provide accurate

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[3] A markup rate of 25% (at all production rates) was used to translate manufacturing cost into expected sales price (inclusive of company profit, overhead, general and administrative expenses, etc.). This rate is based on information garnered from the annual report of a high-volume pressure vessel manufacturer, Hexagon, and is extrapolated from the company's publicly reported gross margin and cost of goods sold. While markup rates can vary substantially company-to-company, even within an industry, Hexagon is judged to be an industry standard in hydrogen and compressed natural gas storage vessels, and thus is thought to be an appropriate markup rate benchmark.

[4] In order to make direct comparison to the DOE targets and align with the DOE terminology for stationary gaseous hydrogen storage costs, the term "tank" is used in Figure 3 to describe the WireTough pressure vessel. Further, "price" and "cost" are used interchangeably for Figure 3, as the purchase cost to a hydrogen forecourt station for a high pressure storage tank is identical to the price WireTough would charge for its product. A table of DOE's cost targets for off-board hydrogen storage, along with descriptions of the components in question, can be found here: https://energy.gov/eere/fuelcells/doe-technical-targets-hydrogen-delivery.

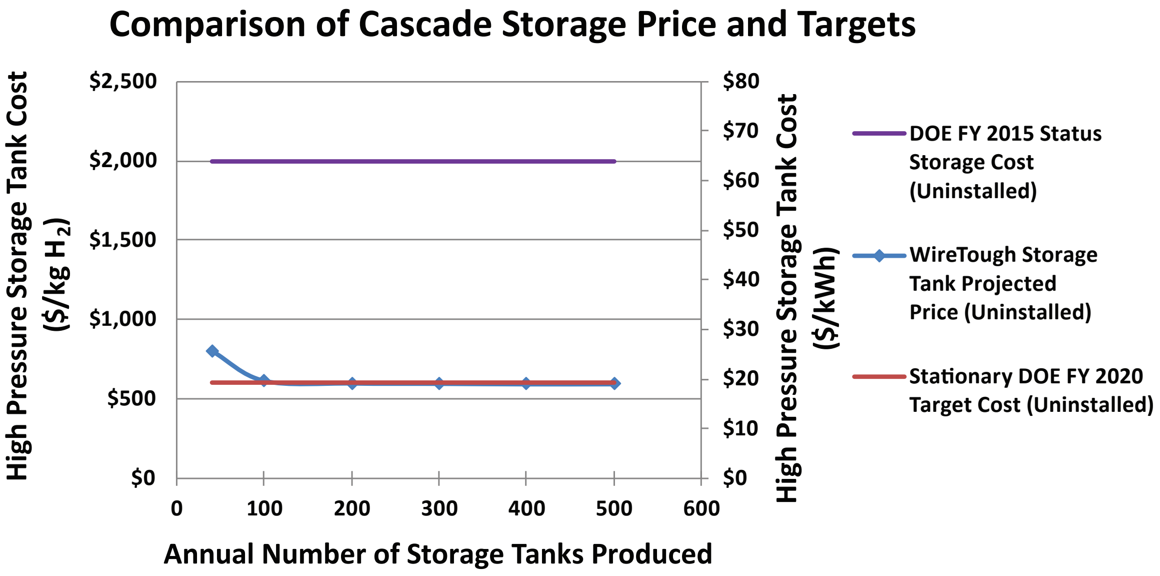

**FIGURE 3.** Comparison of wire-wrapped pressure vessel cost projections to various DOE targets

results because it is closely modeled on the validated high-TRL methodology and includes extensive expert review of assumptions and results.

The WireTough Cylinders LLC wire-wrapped hydrogen storage system appears to be a cost-effective alternative to metal and Type II tanks for stationary high pressure applications. Preliminary analysis projects a pressure vessel cost of ~$600/kg of stored $H_2$ (uninstalled), achieving the 2020 DOE target of $600/kg and surpassing the DOE 2015 status cost of $2,000/kg. The analysis for the wire-wrapped cylinders will continue into the next fiscal year. The remaining steps include external review of the results and documentation of the results. Other future analyses will be conducted once cases are assigned by DOE. Once the review is complete, the results could potentially be used in future H2A forecourt models.

## FY 2017 PUBLICATIONS/PRESENTATIONS

**1.** Brian D. James, Cassidy Houchins, Genevieve Saur, Jennie M. Huya-Kouadio, and Daniel A. DeSantis, “Analysis of Advanced $H_2$ Production Pathways,” presented at the Department of Energy Annual Merit Review Meeting, 7 June 2017, Washington, D.C.