H2A Delivery Analysis and H2A Delivery Components Model

Dr. Olga Sozinova

National Renewable Energy Laboratory

2010 Hydrogen Program Annual Merit Review

June 9, 2010

Project ID # PD015
NREL/PR-560-49745

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NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.
### Overview

**Timeline**

- **Start date:** FY 2004
- **End date:** on-going Project

**Budget**

- Funding: 100% DOE Funded
- FY09: $200K
- FY10: $150K

**Barriers**

- Lack of Hydrogen/Carrier and Infrastructure Option Analysis (3.2 A)
- Gaseous Hydrogen Storage and Tube Trailer Delivery Costs (3.2 F)

**Partners**

- Argonne National Lab
- Pacific Northwest National Lab
- Nexant, Inc.
- TIAx
- GTI
- Chevron
- Air Liquide
- Linde
- DTI
Relevance: Objectives

**Project Objectives**

- **Update and maintain the H2A Delivery Components Model**
- **Provide Cost Analysis on Hydrogen Delivery Infrastructure**
- **Support other models and analysis that include delivery costs**
- **Expand H2A Components Model by designing new components**

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**MYPP**

"**Activities**: Development of the H2A Delivery Components and Scenario Models, MYPP, 2007, p. 3.2-9"

"**Analysis**: Comprehensive cost and environmental analyses for all delivery options as function of demand, MYPP, 2007, p. 3.2-9"

**Outputs**

"**D3. Output to System Analysis and System Integration**: Hydrogen delivery infrastructure analysis results, MYPP, 2007, p. 3.2-29"
Since 2004 – the project introduction – we were following the general H2A approach and guidelines:

- collaborating closely with industry getting and updating costs and tech specs in the models

- keeping consistency of the cost inputs across all H2A models

- employing H2A standard assumptions *

- maintaining models as publicly available

* http://www.hydrogen.energy.gov/h2a_analysis.html#h2a_project
Barrier 3.2 A: Lack of Hydrogen/Carrier and Infrastructure Option Analysis

“Additional analysis is needed to better understand the advantages and disadvantages of the various possible approaches.” (p. 3.2-18)

Barrier 3.2 F: Gaseous Hydrogen Storage and Tube Trailer Delivery Costs

“Approaches include increasing the storage pressure, utilizing cold hydrogen gas, and/or utilizing a solid carrier material in the storage vessel. The same technology approaches could be utilized for gaseous tube trailers making them much more attractive for hydrogen transport and distribution.” (3.2-20)

Milestone 12

“By 2017, reduce the cost of hydrogen delivery from the point of production to the point of use at refueling sites to < $1/gge” (p. 3.2-26)

APPROACH

• Developing new H2 Delivery option: Rail Delivery Components

• Analyzing a possibility to deliver H2 via existing CNG infrastructure

• Building the model capable of calculating delivery costs from multiple sources to multiple demand centers

• Multi-node delivery model will also include storage sharing capability between demand centers, providing overall storage cost decrease

• Analyzing a possibility for delivering H2 by Truck-Trailer in Composite Tubes instead of Metal tubes – increased capacity
<table>
<thead>
<tr>
<th>Milestone</th>
<th>% of completion, as of March 31, 2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>H2A Delivery Components Model Update: finalize changes to the 700 bar and cryo-compressed dispensing options</td>
<td>95% complete expected completion: end of April 2010</td>
</tr>
<tr>
<td>Hydrogen Rail Delivery Cost Analysis</td>
<td>50% complete expected completion: end of FY10</td>
</tr>
<tr>
<td>Multi-node delivery scenario model development, stage 1 and 2</td>
<td>50% complete expected completion: end of June 2010</td>
</tr>
<tr>
<td>Review: go/no go decision on delivering hydrogen via natural gas pipelines</td>
<td>10% complete expected completion: end of FY10</td>
</tr>
</tbody>
</table>
Technical Accomplishments and Progress

Outline

- H2A Components Model Upgrade and Cost Analysis
- Rail Components development and Cost Analysis
- Building new components for GH2 delivery using composite tubes
- Building multi-node delivery scenario model
Technical Accomplishments and Progress

H2A Components Model Upgrade and Cost Analysis
H2A DELIVERY COMPONENTS MODEL OVERVIEW

Relation to Other Models

H2A Delivery Components Model provides costs for hydrogen delivery components
- Excel based (availability to public)
- flexible

- can be used to provide inputs for spatially and temporally detailed models
## Technical Accomplishments and Progress

### H2A Delivery Components Model Upgrade

#### GH2 Refueling Station Upgrade

<table>
<thead>
<tr>
<th>Dispensing Pressure</th>
<th>350 bar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dispensing Type</td>
<td>Cascade</td>
</tr>
<tr>
<td>Tube Pressure (1st)</td>
<td>180 atm</td>
</tr>
<tr>
<td></td>
<td>480 atm</td>
</tr>
<tr>
<td>Tube Pressure (2nd)</td>
<td>180 atm</td>
</tr>
<tr>
<td></td>
<td>480 atm</td>
</tr>
<tr>
<td></td>
<td>180 atm</td>
</tr>
<tr>
<td></td>
<td>480 atm</td>
</tr>
</tbody>
</table>

#### LH2 Refueling Station Upgrade

- **2 dispensing options:**
  - gas
  - liquid or cryo-compressed

### GH2 Tube-Trailer Upgrade

- **2 options for tube pressure:**
  - 180 atm
  - 480 atm
Overview
Technical Accomplishments and Progress

Impact on refueling station upgrade

100 kg/day Refueling Station H2 COST

- Other Costs
- Energy Cost
- Capital Cost

GH2 350 bar-cascade
GH2 700 bar-cascade
GH2 700 bar-booster compressor
LH2 - gas dispensing
LH2 - cryo dispensing
Technical Accomplishments and Progress

H2A Delivery Components Model Upgrade

How much initial investment needed?

Impact on refueling station upgrade

How energy-effective?

100 kg/day Refueling Station CAPITAL COST

100 kg/day Refueling Station ENERGY USE
Technical Accomplishments and Progress

H2A Delivery Components Model Upgrade

Larger Station – Bigger Investment

Station Capital Cost

Near term: 100 kg/day
Mid-term: 400 kg/day
Long-term: 1200 kg/day

cryo-compressed station is the cheapest and has the simplest design

Cryo-compressed station

350 bar-cascade
700 bar cascade
700 bar-booster compressor
LH2-gas dispensing
LH2-cryo-dispensing

Station Size Comparison

Overview

Station Capital Cost

MM $

station capacity, kg/day
The larger the station – the cheaper H2

H2 Cost

Station Size Comparison

H2 A Delivery Components Model Upgrade

Near term: 100 kg/day
Mid-term: 400 kg/day
Long-term: 1200 kg/day

H2 cost drop by $\Delta = 2.5/kg$
Technical Accomplishments and Progress

H2A Delivery Components Model Upgrade

GH2 Truck-Trailer Capacity

<table>
<thead>
<tr>
<th>Truck capacity, kg H2</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
</tr>
<tr>
<td>200</td>
</tr>
<tr>
<td>400</td>
</tr>
<tr>
<td>600</td>
</tr>
<tr>
<td>800</td>
</tr>
</tbody>
</table>

|| Tube Pressure, atm |
|-------------------|
| 180               |
| 480               |

140 % increase

GH2 Truck-Trailer H2 COST
(average station size 100 kg/day)

<table>
<thead>
<tr>
<th>Truck capacity, kg H2</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
</tbody>
</table>

|| Tube Pressure, atm |
|-------------------|
| 180               |
| 480               |

37% drop
Technical Accomplishments and Progress

Rail Components Development and Update
WHY RAIL?

Rail Delivery may be the most economical option for delivering hydrogen made from renewable sources (long distances+high demand)

Example: H2 from Wind

Estimates of Wind Energy Potential in “purple/red band” states*:
86% of Total US Installed Capacity**
(8,989 GW)

Estimated Annual Generation:
32.4 millions GWh

* IA, KS, MN, MT, NE, NM, ND, OK, SD, TX, WY

** 30% capacity factor at 80 m above ground, assumes 5 MW/km2 of installed nameplate capacity

Source: http://www.windpoweringamerica.gov/pdfs/wind_maps.asp
Technical Accomplishments and Progress

H2 Rail Delivery Pathways

Gaseous Hydrogen Rail Delivery

- Gaseous Production Site Terminal
- Gaseous City Gate Terminal
- Gaseous Refueling Station

Liquid Hydrogen Rail Delivery

- Liquid Production Site Terminal
- Liquid City Gate Terminal
- Liquid Refueling Station

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2 independent reviews (by DTI and PPNL) of the H2 Rail Delivery Components were conducted. The comments and suggestions were incorporated in the updated model.

The NREL delivery team collaborated with multiple industry companies in order to refine the input cost and technical data, and to get a better understanding of the logistics of rail delivery:

- freight data, logistics (Union Pacific Railroads)
- railcar leasing costs (GE Rail Leasing)
- intermodal rail crane cost and technical specs (Konecranes Heavy Lifting Company, Paceco)
Technical Accomplishments and Progress

New Components Using Composite Tubes Development

and

Comparative Delivery Cost Analysis
To estimate delivery costs using COMPOSITE TUBES

7 new components were added to the H2A Delivery Components Model

1. GH2 Rail Production Plant Terminal-Composite Tubes (filling up composite tubes)
2. GH2 Rail Transport-Composite Tubes (delivering composite tubes with H2)
3. GH2 Rail City Gate Terminal-Composite Tubes (reloading composite tubes to the truck trailer)
4. Pipeline-GH2 Truck City Gate Terminal-Composite Tubes (pumping H2 into composite tubes)
5. GH2 Truck-Trailer Terminal-Composite Tubes (filling up composite tubes)
6. GH2 Truck Transport-Composite Tubes (accommodating composite tubes delivery)
7. GH2 Refueling Station-Composite Tubes (accommodating changes in tube pressure and truck capacity)

* all full pathway costs involving composite tubes are preliminary
RAIL: From METAL Tubes to COMPOSITE tubes

Increased railcar capacity:
Metal tubes: 2680 kg of H2
Composite tubes: 4400 kg of H2

33% H2 cost reduction for GH2 Rail Delivery

Cost Reduction for H2 Rail Delivery
Overview

Hydrogen Delivery Cost Via Different Pathways

Distance Sensitivity to the Delivery Cost: Composite Tubes

City Demand:
100 tonnes/day

Average refueling station size:
1200 kg/day

GH2: 350 bar dispensing
LH2: cryo-compressed dispensing

LEAST COST PATHWAY
Up to 1500 km – GH2 Truck
Above 1500 km – LH2 Rail
Technical Accomplishments and Progress

Building multi-node delivery scenario model
**Building Multi-Node Scenario Model**

**Multi-Node Delivery**

- **from**
  - multiple plants
  - multiple plants
  - single plant

- **to**
  - single city
  - multiple cities
  - multiple cities

**Flexibility**

- storage sharing
- branched pipeline networks

**Approach**

- Using SERA Model (former HyDS-ME) – geo-resolution and optimization
- Substitute cost curves with the delivery component build-ups inside of SERA
- By applying the above: get the flexibility to place components at different geographical locations
- Calculate optimal network and storage
- Trace network evolution
- Develop optimal multi-node scenarios
Technical Accomplishments and Progress

Building Multi-Node Scenario Model

What is SERA Model?
GIS-based DYNAMIC optimization model determines the optimal production and delivery infrastructure build-outs for hydrogen, given resource availability and technology cost.

Optimal H2 pipeline network build-out example: H2 from Wind Study


Pipeline
Production site
Consumption site

Hydrogen infrastructure at various demand levels.

a. 5%
b. 10%
c. 50%
d. 100%
Stage 1: Build delivery components inside SERA

4 components were coded:

- Pipeline Compressor
- Pipeline Transport
- Geological Storage
- Pipeline-GH2 Truck City Gate Terminal
Future Work
Future Work

Building Multi-Node Scenario Model

FY10

Stage 2: Restructure SERA for allowing branched pipelines

FY11

Stage 3: Optimize Delivery Networks

- use restructured SERA Model to perform calculations for identifying optimal infrastructure layout
- identify possible pipeline branching points and storage sharing points

Stage 4: Develop multi-node delivery scenarios

- use the learning curve form Stage 3 to develop multi-node delivery scenarios
Go/ No Go decision on using natural gas pipelines for delivering hydrogen

Is it feasible to use NG pipelines for delivering hydrogen?

TARGET: Review available studies on adding hydrogen (pure or as a mixture with other gases) to the natural gas pipelines

FOCUS:
- life cycle assessment
- safety
- leakage assessment
- durability
- integrity
- end use: separation, quality
- impacts: environmental and macroeconomic benefits

Milestone Due: Completion expected by the end of FY10
Future Work (cont)

FY10 – FY11

On-Going Efforts
- Update and maintain H2A Delivery Components Model
- Update Rail Delivery components
- Refine delivery components involving composite tubes

Build-up Hydrogen-From-Wind Scenarios
- Identify near term largest demand centers
- Identify potential wind production sites with maximized capacity pertinent to the above demand areas
- Evaluate storage capacity and locations based on actual wind profiles
- Optimize wind farm size for allowing electricity-from-wind use to liquefy hydrogen
- Analyze delivery options for H2 from wind
Collaborations

Industry
- Linde
- Air Products
- GE Rail Leasing
- Lincoln Composites
- Union Pacific Railroad
- Konecranes Heavy Lifting Company
- Paceco Corporation

National Labs
- Marianne Mintz - ANL (Delivery Analysis)
- Amgad Elgowainy – ANL (HDSAM)
- Brian Bush - NREL (SERA)
- Daryl Brown - PNNL (Model Review)
- Darlene Steward – NREL (H2A Production Model)
- Mike Penev – NREL (H2A Power Model)

Other Companies
- DTI (HyPro Model)
- TIAX (Logistics Model)
- GTI
Summary

Relevance
- Project activities follow the DOE H2 Program targets

Approach
- Project follows H2A general approach and guidelines

Accomplishments
- Rail Delivery Components Update with new freight and cost input data
- H2A Components Model Upgrade with 700 bar and cryo-compressed dispensing
- Designed 7 new delivery components for using composite tubes
- Performed comparative cost analysis for various delivery pathways
- Built-up 4 pipeline delivery components into SERA for multi-node scenarios development

Collaborations
Linde, Air Products, GE Rail Leasing, Lincoln Composites, Union Pacific Railroad, Konecranes Heavy Lifting Company, Paceco Corporation, ANL, PNNL, DTI, TIAX, GTI

Future Work
- Continue developing multi-node delivery scenarios: network optimization and scenarios draft
- Assist DOE in developing go/no go decision on the use of CNG infrastructure for delivering hydrogen
- Build-up Hydrogen-From-Wind Scenarios
Supplemental Slides

FOR THE REVIEWERS ONLY
Responses to Previous Year Reviewers’ Comments

• “It was confusing as to why 100,000 of model runs were needed for HyDS-ME”.
  - multiple runs were conducted with HDSAM for data being used in HyDS-ME (SERA) as cost inputs.

• “This project needs calibration with actual installations costs to verify accuracy of predictions”.
  - extensive collaboration with multiple industrial companies during past year allowed us to substantially improve cost input data
Publications and Presentations

Presentations


Posters


Reports

Rail Components Assumptions

Where possible, costs for liquefaction and truck pathways have been applied to develop rail components.

Gaseous H2 is pumped into composite tubes (550 bar) at the Production Terminal. The tubes are loaded to the truck-trailer at the City Gate Terminal.

Liquid H2 is loaded into rail tankers at the Production Terminal, then transported, and reloaded to the liquid trucks at the City Gate Terminal.

It is assumed that a single train leaves daily to supply a certain quantity of hydrogen to a single city.
Rail Components Assumptions

It is assumed that a single train leaves daily to supply a certain quantity of hydrogen to a single city.

Each day, a loaded train is in transit to the city-gate, and a train with empty tanks is returning.
US Railroad Availability

Miles of Road Operated in the U.S. (2006) - 171,077*

Miles of Road Operated Less Trackage Rights - 140,490*

*Source: U.S. Freight Railroad Statistics, Association of American Railroads

“Miles of Road is the aggregate length of roadway, excluding yard tracks and sidings, and does not reflect the fact that a mile of road may include two, three, or more parallel tracks. Miles of road operated less trackage rights, which eliminates double-counting caused by more than one railroad operating the same track, is the measure of the rail network.”*
Rail Freight Cost

Freight information was taken from the 2008 public Carload Waybill. [http://www.stb.dot.gov/stb/industry/econ_waybill.html](http://www.stb.dot.gov/stb/industry/econ_waybill.html)

This data includes commodity code, freight charges, transit charges, miscellaneous charges, number of railcars, shipped weight, distance traveled and many other factors. The ‘freight charges’ for the 2008 waybill include fuel surcharge as described in the federal register ([http://edocket.access.gpo.gov/2008/E8-26570.htm](http://edocket.access.gpo.gov/2008/E8-26570.htm))

The charges (freight, transit and miscellaneous) were summed and divided by the number of railcars to produce the cost per railcar. This was done for both liquid natural gas and hydrogen gas in order to develop useful rates for moving liquid and gaseous hydrogen. These data were then plotted versus distance traveled to see how the rate varied.
Rail Freight Cost

Gaseous H2 Rail Delivery

![Graph showing rail freight cost vs. distance]

- Formula: $y = 1.1624x + 2906.7$
- $R^2 = 0.0521$

- Argon/Hydrogen Gas - Privately Owned Rail Cars
- Argon-Hydrogen Gas - Railroad Owned Rail Cars

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Rail Freight Cost

Liquid H2 Rail Delivery

Freight Rates for LNG

\[ y = 1484.8x^{0.1744} \]

\[ R^2 = 0.0241 \]
Railcar leasing costs

Rail Car Leasing

Pressure tank and flat car leasing data were provided by GE Rail Car Leasing
http://www.ge.com/railservices/products/railequipmentbycartype.html

Leasing rates

- Flat car $450/railcar/month
- Tanker $700/railcar/month
Composite Tubes

TITAN Tank Measurements

<table>
<thead>
<tr>
<th>Property</th>
<th>SI units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water volume</td>
<td>8400 L</td>
</tr>
<tr>
<td>Diameter</td>
<td>1.08 m</td>
</tr>
<tr>
<td>Length</td>
<td>11.6 m</td>
</tr>
</tbody>
</table>

TITAN Module

<table>
<thead>
<tr>
<th>Property</th>
<th>SI units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tanks/module</td>
<td>4</td>
</tr>
<tr>
<td>Total Water Volume</td>
<td>1.08 m</td>
</tr>
<tr>
<td>Module Dimensions</td>
<td>2.44 m<em>2.44 m</em>12.2 m</td>
</tr>
<tr>
<td>Module Weight (1 bar)</td>
<td>14,500 kg</td>
</tr>
</tbody>
</table>

Source:

TITAN™ Lincoln Composites
Pipeline Cost Sensitivity to Distance

City Demand: 100 tonnes/day

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