H2A Delivery Analysis and H2A Delivery Components Model

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National Renewable Energy Laboratory

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Project ID # PD015
NREL/PR-560-49745

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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.
- TIXAX
- 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**

**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**

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](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)
### Milestone

<table>
<thead>
<tr>
<th>Milestone</th>
<th>% of completion, as of March 31, 2010</th>
</tr>
</thead>
</table>
| H2A Delivery Components Model Update: finalize changes to the 700 bar and cryo-compressed dispensing options | 95% complete  
expected completion: end of April 2010                     |
| Hydrogen Rail Delivery Cost Analysis                                     | 50% complete  
expected completion: end of FY10                            |
| Multi-node delivery scenario model development, stage 1 and 2             | 50% complete  
expected completion: end of June 2010                       |
| Review: go/no go decision on delivering hydrogen via natural gas pipelines | 10% complete  
expected completion: end of FY10                            |
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
H2A Components Model Upgrade and Cost Analysis
H2A DELIVERY COMPONENTS MODEL OVERVIEW

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</td>
<td>180 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
### Technical Accomplishments and Progress

#### H2A Delivery Components Model Upgrade

**Impact on refueling station upgrade**

<table>
<thead>
<tr>
<th></th>
<th>GH2 350 bar-cascade</th>
<th>GH2 700 bar-cascade</th>
<th>GH2 700 bar-booster compressor</th>
<th>LH2 - gas dispensing</th>
<th>LH2 - cryo dispensing</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>100 kg/day Refueling Station H2 COST</strong></td>
<td>3.0</td>
<td>4.0</td>
<td>5.0</td>
<td>6.0</td>
<td>7.0</td>
</tr>
</tbody>
</table>

- **Other Costs**
- **Energy Cost**
- **Capital Cost**
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

<table>
<thead>
<tr>
<th>Component</th>
<th>MM $</th>
</tr>
</thead>
<tbody>
<tr>
<td>GH2 350 bar-cascade</td>
<td>0.2</td>
</tr>
<tr>
<td>GH2 700 bar-cascade</td>
<td>0.4</td>
</tr>
<tr>
<td>GH2 700 bar-booster compressor</td>
<td>1.0</td>
</tr>
<tr>
<td>LH2 - gas dispensing</td>
<td>0.8</td>
</tr>
<tr>
<td>LH2 - cryo dispensing</td>
<td>0.6</td>
</tr>
</tbody>
</table>

100 kg/day Refueling Station ENERGY USE

<table>
<thead>
<tr>
<th>Component</th>
<th>MJ/kg H2</th>
</tr>
</thead>
<tbody>
<tr>
<td>GH2 350 bar-cascade</td>
<td>2.0</td>
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<td>LH2 - cryo dispensing</td>
<td>0.0</td>
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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
The larger the station – the cheaper H₂

- 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>Tube Pressure, atm</th>
<th>Truck capacity, kg H2</th>
</tr>
</thead>
<tbody>
<tr>
<td>180</td>
<td>200</td>
</tr>
<tr>
<td>480</td>
<td>800</td>
</tr>
</tbody>
</table>

140% increase

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

<table>
<thead>
<tr>
<th>Tube Pressure, atm</th>
<th>Truck capacity, kg H2</th>
</tr>
</thead>
<tbody>
<tr>
<td>180</td>
<td>3.0</td>
</tr>
<tr>
<td>480</td>
<td>1.9</td>
</tr>
</tbody>
</table>

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

Source: http://www.windpoweringamerica.gov/pdfs/wind_maps.asp

* 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
Gaseous Hydrogen Rail Delivery

Liquid Hydrogen Rail Delivery

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H2 Rail Delivery Components Update

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
Distance Sensitivity to the Delivery Cost: Composite Tubes

**Hydrogen Delivery Cost Via Different Pathways**

- **GH2 Rail**
- **LH2 Rail**
- **Pipeline-GH2 Truck**
- **Pipeline-LH2 Truck**
- **GH2 Truck**
- **LH2 Truck**

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
Building multi-node delivery scenario model
Multi-Node Delivery

- from multiple plants to single city
- multiple plants to multiple cities
- single plant to 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
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

Hydrogen infrastructure at various demand levels.

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
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
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.
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.
H2 Rail Delivery

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.”*

THIS SLIDE IS FOR THE USE OF THE PEER REVIEWERS ONLY—NOT TO BE USED IN MAIN PRESENTATION
Freight information was taken from the 2008 public Carload Waybill.
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)

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 than plotted versus distance traveled to see how the rate varied.
Rail Freight Cost

Gaseous H2 Rail Delivery

$20,000
$15,000
$10,000
$5,000
$0

0 500 1000 1500 2000 2500 3000 3500

Distance (miles)

y = 1.1624x + 2906.7
R² = 0.0521

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

THIS SLIDE IS FOR THE USE OF THE PEER REVIEWERS ONLY—NOT TO BE USED IN MAIN PRESENTATION
Rail Freight Cost

Liquid H2 Rail Delivery

Freight Rates for LNG

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

\[R^2 = 0.0241\]
Rail car 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 * 2.44 m * 12.2 m</td>
</tr>
<tr>
<td>Module Weight (1 bar)</td>
<td>14,500 kg</td>
</tr>
</tbody>
</table>

Source:

![TITAN Tank](TITAN.png)
Pipeline Cost Sensitivity to Distance

Pipeline Costs

City Demand: 100 tonnes/day

Pipeline Transport Cost

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