Hydrogen Delivery Analysis

Dr. Olga Sozinova
National Renewable Energy Laboratory

2011 Hydrogen Program Annual Merit Review
May 10, 2011

Project ID # PD015

THIS PRESENTATION DOES NOT CONTAIN ANY PROPRIETARY, CONFIDENTIAL OR OTHERWISE RESTRICTED INFORMATION

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:** October 2011
  (Project continuation and direction determined annually by DOE)

### Barriers
- Lack of hydrogen/carrier and infrastructure option analysis (3.2 A)
- Gaseous hydrogen storage and tube trailer delivery costs (3.2 F)

### Budget
Funding: 100% DOE Funded
- FY10: $150K
- FY11: $250K

### Partners
- Argonne National Lab
- Pacific Northwest National Lab
- Nexant, Inc.
- TIAx
- GTI
- Chevron
- Air Liquide
- Linde
- DTI
- Power and Energy Inc.
- Lummus Technology, a CB&I Company
- H2Pump LLC
Relevance: Objectives

Project Objectives

- Hydrogen delivery cost analysis
- Update and maintenance of the H2A Delivery Components Model
- Design of new delivery components
- New delivery scenarios development
- Support of the other models with delivery data

MYPP

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

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

Since 2004 – the project introduction – we have followed the general H2A approach and guidelines:

- Collaborating closely with industry to get and update 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
Approach: Barriers Addressed

**Barriers**

**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.” (p. 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)

---

**Multi-Directional Approach**

- **Future big-volume delivery**: analysis of hydrogen delivery by rail
- **No hydrogen-dedicated infrastructure build-up option**: analysis of H2 delivery via existing NG infrastructure
- **Hydrogen as energy carrier**: analysis of the wind energy delivery via producing, liquefying and delivering hydrogen to a major energy demand center
- **New flexible delivery option**: multi-node delivery scenarios development
- **Truck Delivery**: review of the federal and local highway regulations for truck delivery
- **Truck Delivery-new materials**: composite truck trailer delivery analysis
Approach: Milestones

- **Multi-node delivery model development: introduce pipeline branching**
  - June 2010

- **Rail Delivery Cost Analysis**
  - September 2010

- **Analysis of delivering hydrogen via natural gas network**
  - December 2010

- **Composite Truck Delivery Analysis**
  - December 2010

- **Multi-node delivery scenarios development: build-in (code in) truck delivery components**
  - July 2011

- **Analysis of hydrogen as energy carrier: complete wind-to-hydrogen scenarios**
  - September 2011

- DUE:
  - July 2010
  - September 2010
  - December 2010

- Completed Milestones:
  - Multi-node delivery model development: introduce pipeline branching
  - Rail Delivery Cost Analysis
  - Analysis of delivering hydrogen via natural gas network
  - Composite Truck Delivery Analysis

- Progress:
  - 70% complete
  - 20% complete
At NREL, for hydrogen delivery analysis, we use multiple models.

One of them is the H2A Delivery Components Model
- we update and maintain it (it’s one of the tasks of this project)
- we use it for various types of analysis
- data from it are used in various hydrogen models

Let’s take a quick look at it...
H2A Delivery Components Model Overview

- Model is used in several other hydrogen models
  (as delivery cost data source)

Properties
- Calculates hydrogen delivery cost
- Flexible (cost for separate components or the entire pathway)
- Transparent (no password protection)

Also, at NREL, we use the H2A Delivery Components Model in various types of hydrogen delivery analysis
Technical Accomplishments and Progress

Outline

- Rail delivery cost analysis (comparison with other delivery pathways)
- Hydrogen as a carrier for the wind energy: analysis
- Multi-node delivery scenarios development: progress
- Composite truck delivery analysis
- Hydrogen delivery via natural gas pipelines analysis

2010 Analysis Tasks included:
Technical Accomplishments and Progress

TASK 1

Rail Delivery Cost Analysis
In Comparison with Other Delivery Pathways

OUTPUTS: Progress Report to DOE (July 2010), Milestone Presentation to DOE (September 2010)
For what hydrogen market rail is the best delivery option?

We significantly increased demand range for the current analysis, covering hydrogen needs for the early as well as for the mature market.

**Analysis Ranges:**

**City Demand:**
40-2600 tonnes/day*

**Distance To The City:**
60-2200 miles

* For better resolution, only fractions of demands and distances are shown here. For the full ranges, see supplemental slides.

**LH2 Rail** is the least expensive delivery option for the large ranges of distances and demands.

**Analysis Tool:**
H2A Delivery Components Model
Why would we need to deliver hydrogen over long distances?

Generally, renewable hydrogen sources are far away from the demand centers.

Let’s look at the markets closer....
LH2 Rail is the most economic delivery option for renewable hydrogen at early rollout.

For the early market the rail delivery cost is almost flat: \( \sim \$4/kg \text{ H}_2 \)
**Technical Accomplishments and Progress**

**Delivery Cost: Midterm market – 440 tonnes/day**

LH2 Rail is the most economic delivery option for renewable hydrogen at the **midterm**.

For the midterm market the rail delivery cost is almost flat: $3.5/kg H2.

For < 1000 miles: Pipeline

For > 1000 miles: LH2 Rail

What about pipeline?

It can be competitive (up to 1000 miles) if we find the way for **geologic storage** to work.
Delivery Cost: Mature market – 2440 tonnes/day

50 % of market penetration

LH2 Rail and Pipeline are comparable options cost-wise for the mature market.

Investments to the dedicated hydrogen pipeline make sense when 50 % of market penetration is reached.

Analysis Tool: H2A Delivery Components Model

City Demand: 2440 tonnes/day

Total delivery cost for various pathways

distance to the city gate (miles)

Distance:
- 600 miles
- 1200 miles
- 1800 miles

Delivery Components Model:
- pipeline-LH2 truck
- LH2 truck
- LH2 Rail
- GH2 truck-liquid storage
- pipeline-GH2 truck-geo storage
- GH2 truck-geo storage
- GH2 Rail-Metal Tubes
- GH2 Rail-Composite Tubes

Refueling station capacity = 1200 kg/day
US Railroads Congestion Review

If rail is a player cost-wise, is it really viable capacity-wise?

To answer this question, we reviewed the Association of American Railroads study “National Rail Freight Infrastructure Capacity and Investment Study” *

Technical Accomplishments and Progress

US Railroads Congestion Review

Train Volumes Compared To Current Capacity

<table>
<thead>
<tr>
<th>LOS Grade</th>
<th>Description</th>
<th>Volume/Capacity ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Below Capacity</td>
<td>0.0 to 0.2</td>
</tr>
<tr>
<td>B</td>
<td>Near Capacity</td>
<td>0.2 to 0.4</td>
</tr>
<tr>
<td>C</td>
<td>Above Capacity</td>
<td>0.4 to 0.7</td>
</tr>
<tr>
<td>D</td>
<td>Below Capacity</td>
<td>0.7 to 0.8</td>
</tr>
<tr>
<td>E</td>
<td>At Capacity</td>
<td>0.8 to 1.0</td>
</tr>
<tr>
<td>F</td>
<td>Above Capacity</td>
<td>&gt;1.0</td>
</tr>
</tbody>
</table>

88% - below capacity
12% - near or at capacity
1% - above capacity

AAR determined the areas of railroad improvements by 2035

**Line expansion:**
- Upgrades to mainline tracks and signal control systems
- Improvements to significant rail bridges and tunnels
- Upgrades to Class I railroad secondary mainlines and branch lines to accommodate 286,000-pound freight cars
- Upgrades to short line and regional railroad tracks and bridges to accommodate 286,000-pound freight cars

**Facility expansion:**
- Expansion of carload terminals, intermodal yards, and international gateway facilities owned by railroads
- Expansion of Class I railroad service and support facilities such as fueling stations and maintenance facilities

**Total Cost of Improvements**

Total Cost of Improvements was estimated as $147.5 Billions of 2007 Dollars

*2035 train volumes were projected using economic growth and commodity forecasts from the U.S. DOT’s Freight Analysis Framework (FAF Version 2.2)*
Technical Accomplishments and Progress

Hydrogen as a carrier for the wind energy: analysis

OUTPUT: Publication with ANL (in review)
Technical Accomplishments and Progress

Hydrogen as Energy Carrier: Wind-to-Hydrogen Scenarios

In FY10 NREL assessed 2 short-term scenarios:
- grid-independent with seasonal geo storage
- grid-connected

More scenarios will be assessed in FY11

FY10 Scenarios Goal:
- 40,000 kg/day of H2
- wind farm near Albuquerque
- liquefy
- deliver to the Los Angeles area

Analysis Tools:
- Modified NREL Fuel Cell Power Model
- H2A Hydrogen Delivery Components Model

Technical Accomplishments and Progress

Hydrogen as Energy Carrier: Wind-to-Hydrogen Scenarios

NREL Western Wind Resource Data* were used in the analysis.

NREL Fuel Cell Power Model** was used for wind farm optimization and hydrogen production analysis.

H2A Delivery Components Model is used for delivery costs.


** NREL Fuel Cell and Power Model: [http://www.hydrogen.energy.gov/fc_power_analysis.html](http://www.hydrogen.energy.gov/fc_power_analysis.html)

Each data set includes 10 minute wind speed and wind turbine electrical output data for an aggregate of 10 3MW-rated power wind turbines.
Technical Accomplishments and Progress

Hydrogen as Energy Carrier: Wind-to-Hydrogen Scenarios

NREL GIS team data were used for geologic storage and transmission lines locations.

Wind farm location in relationship to Albuquerque and the nearest transmission line.

Wind Farm Proximity to Potential Hydrogen Geologic Storage Reservoirs (Saline) and major US Cities.

Carbon sequestration data was obtained from NETL via reactcarb.org.
Wind-to-LH2 Scenarios Results

- **Grid-independent:** $11.3/kg of dispensed H2
  - Production: $6.7/kg
  - Liquefaction, storage and delivery: $4.6/kg
  (rail, 1200 kg/day ref. station)

- **Grid-connected:** $10.6/kg of dispensed H2
  - Production, storage: $6.6/kg
  - Liquefaction and delivery: $4.0/kg
  (rail, 1200 kg/day ref. station)

**Issues:**
90 days of seasonal storage is needed. Geologic hydrogen storage is not that feasible and requires further research and analysis.

**Cost Reduction Possibility:**
Production cost is highly dependent on wind turbine capital cost (which has high market volatility). Sensitivity analysis shows that H2 cost can be reduced by $2/kg in the case of market lower turbine cost (30% less than average).

Details can be found at: “Liquid Hydrogen Production and Delivery from a Dedicated Wind Power Plant”, October 2010 Report to DOE (currently in review)
Technical Accomplishments and Progress

TASK 3

Multi-node delivery scenarios development: progress

OUTPUTS: Progress Report to DOE (May 2010), Milestone Presentation to DOE (June 2010)
Building Multi-Node Delivery Scenarios

Multi-Node Delivery
from to
multiple plants single city
multiple plants multiple cities
single plant multiple cities

Benefits
- Delivery Flexibility (ex: storage, pipeline, or plant sharing)
- Geographic resolution

Approach
Use SERA model
Considering that SERA is not ready yet for this type of scenarios,
Enhance SERA delivery block:
- add pipeline branching
- substitute cost curves by delivery components coded directly into SERA

Tools Used:
- SERA Model
- H2A Hydrogen Delivery Components Model
SERA is a very powerful tool.
At NREL, we use it for various types of analysis.

Here, we will consider the development of multi-node delivery scenarios with the help of SERA only.
Building Multi-Node Delivery Scenarios

What is SERA Model?

NREL DYNAMIC optimization model:
- GIS-based
- Java-coded software
- Determines the optimal production and delivery infrastructure build-outs
- Traces infrastructure evolution

SERA Graphical Output Example

NAS Demand Assumptions
- Basic Geodata
- Census & FHWA Data
- H2A Production
- H2A Delivery Components

HyDRA
OGC-Compliant Geospatial Database
SQL-based data manipulation

SERA Structure
- Optimization
- GIS Visualization
- Visual Analytics
- Maps
- Charts & Tables

SERA User Interface Snapshot

Technical Accomplishments and Progress

NREL DYNAMIC optimization model:
- GIS-based
- Java-coded software
- Determines the optimal production and delivery infrastructure build-outs
- Traces infrastructure evolution

SERA Graphical Output Example

HyDRA
OGC-Compliant Geospatial Database
SQL-based data manipulation

SERA Structure
- Optimization
- GIS Visualization
- Visual Analytics
- Maps
- Charts & Tables

SERA User Interface Snapshot

Technical Accomplishments and Progress
Building Multi-Node Delivery Scenarios

This Year Subtasks Toward Multi-Node Delivery Scenarios Development:

- Enhance SERA pipeline buildup algorithm: introduce branching

- Use H2A Delivery Components (Excel-based) to code them directly into SERA delivery block (Java-based)

Tools Used:

- SERA Model
- H2A Hydrogen Delivery Components Model
Technical Accomplishments and Progress

Building Multi-Node Delivery Scenarios

Demonstration of the pipeline network evolution at the Midwestern region. Years 2030-2050.

Subtask 1 is completed: pipeline branching is introduced

Remarks: only SMR and coal gasification are chosen as hydrogen production technologies for this demonstration to save on CPU time. Normally, SERA considers all H2 production technologies available in H2A.
Building Multi-Node Delivery Scenarios

Progress on the Subtask 2:
14 H2A Delivery Components were coded into SERA

Testing Process:
10 of 14 components are tested as of March 11, 2011

Tools Used:
- SERA Model
- H2A Hydrogen Delivery Components Model

SERA Development Interface Snapshot
(components testing XML codes)
Technical Accomplishments and Progress

TASK 4

Composite Truck Delivery Analysis

OUTPUTS: Draft Report to DOE (December 2010), Milestone presentation to DOE (December 2010)
Composite Truck Delivery Analysis

Is composite truck currently competitive for renewable H2 delivery?

Long Distance Delivery (600 miles)
GH2 RAIL vs GH2 Truck

Composite truck can be competitive for renewable hydrogen delivery (long-distance) only in the case of allowing for the second trailer.

Analysis Tool:
H2A Delivery Components Model

Current technology:
550 kg H2/truck

Other technologies are available (up to 900 kg/truck), but they are currently more expensive.
We can significantly drop the cost of transporting H2 by truck, if
- use 2 trailers per truck (induces larger refueling station footprint), or
- raise tube pressure to 550 bar
Composite Truck Delivery Analysis

Can we even afford 2 bundles (or, 2 trailers) per truck on the US highway system?

To answer this question, we reviewed Federal (FHWA) and State (ISTEA) highway regulations (size and weight limitations per truck)

CONCLUSIONS IN BRIEF

In many “renewable” states* it’s possible to carry 2 bundles (or, 2 trailers) per truck

* AK, AR, CO, ID, IN, IA, KS, MO, MT, NV, ND, OH, SD, UT, NM, NY, WY, OR

For reviewers: see details in supplemental slides

Details can be found at: “Analysis of Hydrogen Delivery By Gaseous Composite – Tube - Truck”, NREL Report to DOE, December 2010
Technical Accomplishments and Progress

Hydrogen Delivery Via Existing Natural Gas Pipelines: Analysis

OUTPUTS: Draft Report to DOE (December 2010),
NREL Published Report (currently in review)
Hydrogen Delivery Via Existing Natural Gas Pipelines

Scope of Analysis:

- Review of NG pipelines system in the US
- Review of European (NaturalHy Project) and US studies
- Hydrogen extraction technologies overview
- Cost assessment of hydrogen extraction
NREL reviewed the U.S. Natural Gas Pipeline Network, based on data from the Energy Information Administration, Office of Oil and Gas Division.

**Scope of US NG Network Review:**

- US Major Transportation Corridors
- Interstate Grid
- Intrastate Grid
- Capacity and Utilization
- Underground Storage
- Transmission Pipelines
- Distribution Pipelines

Details can be found at: “Hydrogen Delivery in Natural Gas Networks”, NREL Publication (currently in review)
## Hydrogen Delivery Via Existing Natural Gas Pipelines

### CONCLUSIONS IN BRIEF

#### Benefits

- Air quality improvements

#### Safety

- Up to 20% H2 is safe for both transmission and distribution pipelines

#### Leakage

- PE distribution mains: Volume leakage rate is about 3 times higher for H2 than for NG

#### Durability

- **Transmission:** No major concern on H2 induced failures
- **Distribution:** no major concern on aging

#### Integrity

- **Transmission:** modifications are not significant (< 50% H2)
- **Distribution:** modified integrity management is required

---

Details can be found at: “Hydrogen Delivery in Natural Gas Networks”, NREL Publication (currently in review)
NREL Assessment of Separation Technologies

NREL assessed three major separation technologies

- Membranes
- Electrochemical Separation
- Pressure Swing Adsorption (PSA)

For reviewers: see details in supplemental slides

CONCLUSION IN BRIEF

PSA is the most commercially ready technology

Details can be found at: “Hydrogen Delivery in Natural Gas Networks”, NREL Publication (currently in review)
Hydrogen Delivery Via Existing Natural Gas Pipelines

NREL Assessment of Cost of Hydrogen Extraction by PSA Unit *

Hydrogen extraction cost is $2-$6.5/kg, depending on a recovered volume

Compressor (for NG recompression) capital cost is 64% of the total capital cost of the extraction plant

* Based on Nth plant assumption (mature technology)
Hydrogen Delivery Via Existing Natural Gas Pipelines

NREL Assessment of Cost of Hydrogen Extraction by PSA Unit *

What if we avoid recompression?
Extract Hydrogen at the Pipeline Pressure Reduction Facility

PSA Hydrogen Extraction Cost At Pressure Reduction Facility (from 300 psi to 30 psi)

- Hydrogen extraction cost is $0.2-$1.0/kg. Much better!

Issue: number of these facilities is limited

* Based on Nth plant assumption (mature technology)
Future Work

- Update and maintain H2A Delivery Components Model
  - $2007
  - 2010 and 2020 technologies

- Continue to develop wind-to-hydrogen scenarios
  - various storage types
  - gaseous delivery
  - long-term

- Continue on multi-node scenario model development
  - complete delivery components coding and testing
  - multi-node pathways constructing

- Analyze the total pathway cost for delivering hydrogen via NG pipelines
  - pumping in, transporting, extracting and dispensing

Milestone due

- September 2011
- July 2011
- FY2012
- FY2012
## Collaborations

### Industry
- Linde
- Air Products
- GE Rail Leasing
- Lincoln Composites
- Structural Composites Industries (SCI)
- Union Pacific Railroad
- Konecranes Heavy Lifting Company
- Paceco Corporation
- Power and Energy Inc.
- Lummus Technology, a CB&I Company
- H2Pump LLC

(technical and cost inputs)

### 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)

(data exchange and review)

### Other Companies
- DTI
- TIAx
- Gas Technology Institute (GTI)

(data exchange and review)

(subcontractor)
Relevance
- Project activities follow the DOE H2 Program targets

Approach
- Project follows H2A general approach and guidelines

Accomplishments
- Rail delivery analysis in comparison with other delivery options, US railroad congestion review
- Wind-to-liquid hydrogen scenarios assessment
- Multi-node delivery scenarios development: pipeline branching algorithm and delivery components coding and testing
- Composite truck (550 kg H2) cost analysis, and Federal and State highway regulations review
- Analysis of delivering hydrogen in existing NG pipelines

Collaborations
Linde, Air Products, GE Rail Leasing, Lincoln Composites, Union Pacific Railroad, Structural Composites Industries (SCI), Konecranes Heavy Lifting Company, Paceco Corporation, ANL, PNNL, DTI, TIAX, GTI, Power and Energy Inc., Lummus Technology- CB&I Company, H2Pump LLC

Future Work
- Update and maintain H2A Delivery Components Model
- Continue on developing multi-node delivery scenarios: pathways development
- Develop more wind-to-hydrogen scenarios with various storage types, and long-term demands
- Analyze the full pathway cost for delivering hydrogen in NG pipelines