Hydrogen Delivery Infrastructure Options Analysis

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Project ID: PD12 Kelly
Overview

Timeline
- Start – June 2005
- Finish – March 2008
- 70 percent complete

Budget
- Total project funding
  - DOE - $1,886,504
  - Contractor - $0
- 2005 - $570,000
- 2006 - $745,000
- 2007 - $551,000

Barriers
- Delivery systems analysis
- Novel solid / liquid transport
- Delivery storage costs

Targets
- 2007: Delivery infrastructure criteria
- 2012: <$1.70/gge delivery + dispensing
- 2017: <$1.00/gge delivery + dispensing

Partners
- TIAX
- NREL, ANL, PNNL
- GTI
- Chevron
- Air Liquide
- Pinnacle West
Objectives

- Refine technical and cost data in H2A Component and Scenario Models to incorporate additional industrial input and evolving technology improvements
  - Significant data additions
  - Delivery system storage analysis and optimization
- Explore new options to reduce hydrogen delivery cost, including novel carriers
- Expand H2A Component and Scenario Models to include new options leading to Version 2 models
- Provide bases to recommend hydrogen delivery strategies for initial and long term use of hydrogen as a major energy carrier
Approach

- Compile data on liquid and gas fuel distribution methods.
- Develop improved and expanded energy requirements, capital costs, and operating costs for 19 hydrogen delivery pathways.
- Evaluate capability of existing infrastructure to deliver hydrogen.
- Assess greenhouse gas and pollutant emissions for each delivery option.
- Compare and rank delivery options.
- Recommend hydrogen delivery strategies as a function of market development.
Delivery Options

1: Dedicated pipelines for hydrogen gas delivery
2: Convert existing natural gas and oil pipelines to hydrogen gas delivery
3: Blend hydrogen with natural gas for pipeline transmission; separate at city gate
4: Truck delivery of hydrogen gas
5: Truck transport of hydrogen liquid
6: Novel hydrogen carriers
7: Mixed mode pathways
Project Status/Accomplishments

June 2005 to May 2006

- Analyzed hydrogen/natural gas mixing, transmission, and separation utilizing existing natural gas pipeline infrastructure
- Evaluated refurbished natural gas pipelines for hydrogen transmission
- Assembled industrial and commercial data for performance and cost improvements to H2A models and reviewed the V1 H2A Delivery Model
Project Status/Accomplishments

May 2006 to May 2007

- Analysis of market demand and supply variations and delivery systems optimization for storage, compression, dispensing
- Improved hydrogen compressors characterization: capacities and costs at refueling site and terminals
- Improved storage vessel designs and costs at refueling site and terminals
- Improved estimates for hydrogen liquefaction energy requirements and plant costs
- Modeled variable refueling site sizes: compressor capacities, cascade storage capacities, number of dispensers, electric power supply, etc.
- Revamped distribution pipeline costs
- Analyzing novel carrier pathway options
Analysis of market demand and supply variations

- **Supply Side Variations:**
  - Central Production Plant Outages
    - Scheduled yearly maintenance: Typically 5 to 10 consecutive days each year
    - Unscheduled maintenance outages: Indeterminate time and length
    - Natural disasters: A few days?

- **Demand side variations**
  - Hourly at refueling sites
  - Day to day at refueling sites
    - Friday is 8% higher than the average
  - Winter/Summer demand variation
    - Summer is 10% above average; winter is 10% below average
Analysis of Storage Options and Costs

- Storage Problem
  - Production plants operate at constant rate, but demand varies

- Storage Options
  - Geologic gas storage
    - Low cost for very large amounts of hydrogen
    - May not be conveniently located
  - Liquefaction and liquid storage: Second best for large quantities
  - GH2 Tanks: Highest cost, but efficient for small volumes

- Storage and compression can add significant cost to hydrogen delivery
- Need to find the optimum storage solution
Geologic GH2 and Liquefaction/LH2 Storage

- Geologic gas storage costs: Two orders-of-magnitude less than steel pressure vessels

- Liquefaction and liquid storage costs: Nominal $45/kg of hydrogen stored for large production plants and storage capacities

- Steel pressure vessels: $1,300 to $1,500/kg of hydrogen stored
GH2 Hydrogen Vessel Storage

Vessel design options

- **SA516, Grade 70; 17,500 psi allowable stress**
  - 48 in. diameter; 24 ft. long; 2.5 in. wall thickness
  - $1.91/lb of steel; $980/kg of hydrogen stored

- **SA36; 14,000 psia allowable stress**
  - 48 in. diameter; 24 ft. long; 3.25 in. wall thickness
  - $1.78/lb of steel; $1,223/kg of hydrogen stored

- **SA372, Grade J, Class 70; 40,000 psi allowable stress**
  - 24 in. diameter; 25 ft. long (2,800 psi $H_2$ pressure)
  - $2.75/lb of steel; $596/kg of hydrogen stored
GH2 Vessels as Hourly Storage

Capital and operating cost versus pressure

Production Plant Storage Pressure, psia

Total Storage Cost, $1000
GH2 Vessel Storage: Conclusions

- **Gas storage vessel design**
  - SA516, Grade 70; 2,500 psia; 2.5 in. wall thickness
  - 4.1 ft. diameter, 24.9 ft. long, 91 kg hydrogen capacity
  - $2.30/lb of steel; $816/kg of hydrogen stored

- **Recommended inputs to H2A model**
  - $1,340/kg of hydrogen stored, including shipping, auxiliaries, installation, engineering, site preparation, contingency, and permit fees
  - Independent of capacity

>90% effective for storage
Refueling Site Cascade Charging/Storage

- ASTM SA372, Grade J, Class 70 low alloy steel
- $843/kg budgetary price from CP Industries
- Vessels are 16 inches diameter, 30 feet long
  - 6250 psia vessel stores 21.3 kg
  - 5000 psia vessel stores 19.4 kg
  - 4000 psia vessel stores 17.2 kg
- $843/kg of hydrogen stored unit price assumed for each vessel
- With shipping, $926/kg of hydrogen stored
Refueling Site Cascade Charging/Storage

Recommended inputs to H2A models
- $926/kg for vessel assembles, delivered
- $268/kg for storage auxiliaries
- $266/kg for engineering, site preparation, contingency, and permit fees
- $1,460/kg of hydrogen stored total investment cost

Designed for vehicle dispensing:
Only ~30% effective for storage
Compressor Costs for Storage and Dispensing

Large reciprocating and refueling site compressors

Small Compressors

y = 5.047x + 22.77

Large Compressors

y = 38,414 x^{0.6089}

Motor rating, kWe

Total Installed Cost, $1000

Capacity, kg/hr

Reciprocating
Diaphragm

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Refueling Site Design and Optimization

Refueling demand shifted to beginning of each hour

Fraction of peak delivery

Time

12:00 AM  2:00 AM  4:00 AM  6:00 AM  8:00 AM  10:00 AM  12:00 PM  2:00 PM  4:00 PM  6:00 PM  8:00 PM  10:00 PM  12:00 AM

Chevron  TIAX

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Refueling Site Design and Optimization

Required combinations of refueling site compressor and cascade charging system capacities

- 1400 kg/day - Low
- 1800 kg/day - High
- 2142 kg/day - Peak
- 2000 kg/day - Low
- 2200 kg/day - Mid
- 2400 kg/day - High
- 2851 kg/day - Peak
- 3400 kg/day - Mid
- 3600 kg/day - High
- 4284 kg/day - Peak
Refueling Site Design and Optimization

Refueling site optimization

Capital and installation cost, $1000

Peak compressor flow rate / Average station flow rate

- 1400 kg/day - Low
- 1800 kg/day - High
- 2142 kg/day - Peak
- 2000 kg/day - Low
- 2200 kg/day - Mid
- 2400 kg/day - High
- 2851 kg/day - Peak
- 3400 kg/day - Mid
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System Optimization for Hourly Demand Profile

- Optimized compressor/cascade storage system does not have sufficient storage for full daily profile
  - Need an additional 0.3 days of storage
- Pipeline Pathway
  - Low pressure storage (2500 psi) offers the most efficient and cost effective means for providing storage
  - Terminal: Storage compressor, plus low cost land
  - Refueling site: One compressor may be suitable; additional land for low pressure storage vessel
- Gas Tube Trailer, and Liquefaction/Liquid Truck Pathway
  - Tube trailer, or liquid truck, at the refueling site provides 0.3 days of storage
# Novel Hydrogen Carriers

<table>
<thead>
<tr>
<th>Novel Delivery</th>
<th>Example Materials</th>
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<tbody>
<tr>
<td>Liquid</td>
<td>• Liquid HC (APCI Material)</td>
</tr>
<tr>
<td></td>
<td>• Ammonia-Borane</td>
</tr>
<tr>
<td>Solid-Liquid Slurry</td>
<td>All with liquid carrier:</td>
</tr>
<tr>
<td></td>
<td>• Chemical Hydrides (SBH, MgH₂)</td>
</tr>
<tr>
<td></td>
<td>• Metal Hydrides (NaAlH₄)</td>
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<tr>
<td></td>
<td>• Carbons?</td>
</tr>
<tr>
<td>Bricks</td>
<td>• Chemical Hydrides, Alanates?</td>
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<tr>
<td></td>
<td>• Metal Hydrides</td>
</tr>
<tr>
<td></td>
<td>• Carbons</td>
</tr>
<tr>
<td>Flowable Powder</td>
<td>• Metal Hydrides</td>
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<tr>
<td></td>
<td>• Chemical Hydrides</td>
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<tr>
<td></td>
<td>• Carbons</td>
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</tbody>
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The primary challenges for all novel carriers include cost, density (weight and volume), and energy requirements.
**Major cost contributors:** initial capital, continuous material, and energy

- Today's processes may not recycle all spent material

- Transportation of the carrier and spent material in same truck

- Cost inputs include H2 yield, capital costs, and delivery distance

- May include carrier and spent material storage and dispensing (loading and off-loading)

- Alternately, compressed hydrogen dispensing

**Novel Carriers - Modified H2A Tabs**
Carrier Objectives, and Some Major Issues

- Complete a first-phase screening of materials and pathways to determine which are clearly not viable.
- For carriers deemed viable, create H2A-like tools to consistently evaluate various novel carrier options.
- Important to avoid making pathway decisions based on the limitations of present technologies and materials.
- Major issues that remain:
  - Are pipelines viable methods of novel carrier transport?
  - What is the overall time (days) of a carrier cycle?
  - What are the effects of labor costs?
  - What is the maximum feasible brick weight?
  - Can we better define the equipment used to transport powders?
Distribution Pipeline Costs

- Collected historical Oil & Gas Journal data, and surveyed for current urban and downtown data
- Verified that historical natural gas pipeline cost data are representative of hydrogen pipeline costs
- Better defined regulatory issues and other potential concerns in urban areas and their impact:
  - Potential need for odorants or other leak detection technology
  - Allowable operating pressures
  - Right-of-Way availability
Summary

- H2A model inputs on systems and components optimization, performance, and cost
  - Large hydrogen compressors
  - Refueling site compressors
  - Refueling site cascade storage
  - Hydrogen liquefaction plants
  - Gas storage terminals
  - Distribution pipelines within a city
  - Land areas
  - Variable sized refueling sites: 100-6,000 kg/day average daily capacity
  - Working on novel carriers
Summary - Continued

- Analysis of market demand and supply variations and delivery systems optimization for storage, compression, and dispensing
  - Seasonal demand variations and production plant maintenance: Gas geologic storage, or liquefaction and liquid storage at terminal or plant
  - Daily and hourly refueling site: Low pressure (2500 psi) storage at the fueling site or terminal. Could also use oversized transmission pipeline (if >100 miles of transmission pipeline)

Version 2.0 of the H2A Models will be Published later this year

All this applies to current costs: H2A Models will allow the same principles and optimization for inputted future costs and targets
Future Work

- Complete novel carrier options analyses and incorporate as appropriate
- Incorporate GREET and explicit results for pathway energy efficiency, greenhouse gas and criteria pollutant emissions
- Recommend delivery strategies at each market penetration