Hydrogen Delivery Options and Issues

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DOE

August, 2006
Hydrogen Delivery

Scope

• From the end point of central or distributed production (300 psi H2) to and including the dispenser at a refueling station or stationary power site
  – GH2 Pipelines and Trucks, LH2 Trucks, Carriers

<$1.00/kg of Hydrogen by 2017
H2 Delivery Current Status

• Technology
  – GH2 Tube Trailers: ~340 kg, ~2600 psi
  – LH2 Trucks: ~3900 kg
  – Pipelines: up to 1500 psi (~630 miles in the U.S.)
  – Refueling Site Operations (compression, storage dispensing): Demonstration projects

• Cost (Does NOT include refueling Site Operations)
  – Trucks: $4-$12/kg
  – Pipeline: <$2/kg
H2A Analysis

• Consistent, comparable, transparent approach to hydrogen production and delivery cost analysis
• Excel spreadsheet tools with common economic parameters, feedstock and utility costs, and approach
• Project Team
  – Production: DTI, TIAx, Technology Insights, PNNL, NREL, ANL
  – Delivery: U.C. Davis, ANL, PNNL, NREL
• Key Industrial Collaborators
  Eastman Chemical  Ferco
  AEP  Thermochem
  Entergy  GE
  Framatome  Stuart Energy
  APCi  Chevron
  Praxair  Exxonmobil
  BOC  BP
H2A Delivery Goals

- Develop spreadsheet database on delivery system component costs and performance: Component Model
- Develop delivery scenarios for set of well defined “base cases” that span major markets and demand levels. Scenario Model (HDSAM)
- Estimate the cost of H₂ delivery for base cases with current (2005 costs) and at Research Targets
List of Delivery Components

- Compressed Hydrogen Gas Truck (Tube trailer)
- Compressed Hydrogen Gas Truck Terminal
- Liquid Hydrogen Truck
- Liquid Hydrogen Truck Terminal
- H2 Transmission Compressor
- H2 Forecourt Compressor
- Hydrogen pipelines
- H2 Liquefier
- LH2 Storage Tank
- Gaseous H2 Storage “Tank”
- Gaseous H2 Geologic Storage
- Dispenser
- Forecourt: GH2
- Forecourt: LH2
Three-Quarters of the US Population Reside in Urbanized Areas
Hydrogen Plants can be Located Relatively Near the Market demand

Nearly all areas East of the Mississippi and West of the Rockies are within 200 highway miles (320 km) of large urbanized areas
Overview of the H2A Delivery Scenario Model

Scenario Definition

Components and Other Sub-Models

Results

Penetration

0 25 50 75 100

Market

Mode

Pipeine Module

Truck Module

Delivery Cost

Capital Operating Energy

Transport Storage Packaging

Cumulative Cash Flow

Inputs
Current Scenario Model

• Predefined demand based on:
  - Market (urban or interstate/rural)
  - Penetration of hydrogen-fueled LDVs (%)
  - Single delivery mode
  - 100 kg/day or 1500 kg/day Forecourts

• Delivery mode defined by user
  - Pipeline with geologic storage
  - Liquid hydrogen (LH2) via terminal and truck
  - Compressed hydrogen (CH2) truck via terminal and truck (18 MPa and 50 MPa)

Components tabs linked so pathway capacities reflect losses and availabilities
Current Urban Hydrogen Delivery Costs

Urban: 1 M people, Plant 62 miles from city gate

Current Urban

- Pipeline
- Pipeline Fit
- Liq H2
- Liq H2 Fit
- GH2 Tube Trailer

Power (Pipeline Fit)
Power (Liq H2 Fit)

Current Urban Hydrogen Delivery Costs:

- $1.62
- $1.90
- $2.14
- $2.36

% Penetration

0% 10% 20% 30% 40% 50% 60% 70% 80% 90% 100%
Urban Hydrogen Delivery Costs at Research Targets

Urban: 1 M people, Plant 62 miles from city gate

Market Penetration (%)

$/kg H2

Pipeline Fit
Liq H2 Fit
GH2 Tube Trailer Fit

Pipeline
Liq H2
GH2 Tube Trailer

$1.06
$1.68
$1.95

$1.0
$1.18
$1.95
Current Rural Hydrogen Delivery Costs

Rural: 300 mile cross

- Pipeline
- Pipeline Fit
- Liq H2
- Liq H2 Fit
- GH2 Tube Trailer

Market Penetration (%) vs. $/kg H₂

- $3.34 at 50% market penetration
- $2.61 at 60% market penetration
- $2.41 at 90% market penetration
- $2.26 at 100% market penetration

$0.0 to $30.0 on the y-axis.
Current Liquid H2: 50% Market Penetration

City: 250k people, Plant 62 miles from city gate

$/kg H2

- LH2 Truck
- Liquefier
- Terminal
- LH2 Station
- Total

Energy & Fuel
O&M
Capital
Current* Tube Trailer: 50% Market Penetration

City: 250k people, Plant 62 miles from city gate

<table>
<thead>
<tr>
<th></th>
<th>Energy &amp; Fuel</th>
<th>O&amp;M</th>
<th>Capital</th>
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<tbody>
<tr>
<td>Terminal</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>High Pressure Tube Trailer</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GH2 Station</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
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</table>
Current Pipeline: 50% Market Penetration

City: 250k people, Plant 62 miles from city gate

$/kg H2

Transmission Pipe
Distribution Pipe
Central Compressor
Geologic Storage
GH2 Station
Total

Energy & Fuel
O&M
Capital
## Current Refueling Site Costs

### 1500 kg/day Station

<table>
<thead>
<tr>
<th></th>
<th>Compressor</th>
<th>Other (Storage)</th>
<th>Dispenser</th>
<th>Total</th>
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</thead>
<tbody>
<tr>
<td>Total Cost ($/kg of H2)</td>
<td>$0.50</td>
<td>$0.30</td>
<td>$0.05</td>
<td>$0.85</td>
</tr>
<tr>
<td>Capital Cost Contribution</td>
<td>$0.26</td>
<td>$0.13</td>
<td>$0.05</td>
<td>$0.44</td>
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<tr>
<td>Energy Cost Contribution</td>
<td>$0.18</td>
<td>$0.00</td>
<td>$0.00</td>
<td>$0.18</td>
</tr>
<tr>
<td>Other Costs Contribution</td>
<td>$0.06</td>
<td>$0.17</td>
<td>$0.00</td>
<td>$0.23</td>
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<tr>
<td>Installed Capital Cost ($k)</td>
<td>$460</td>
<td>$293</td>
<td>$81</td>
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<tr>
<td>Total Capital cost ($k)</td>
<td></td>
<td></td>
<td></td>
<td>$1,014</td>
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</table>

### 100 kg/day Station

<table>
<thead>
<tr>
<th></th>
<th>Compressor</th>
<th>Other (Storage)</th>
<th>Dispenser</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Cost ($/kg of H2)</td>
<td>$0.71</td>
<td>$1.39</td>
<td>$0.24</td>
<td>$2.34</td>
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<tr>
<td>Capital Cost Contribution</td>
<td>$0.36</td>
<td>$0.34</td>
<td>$0.24</td>
<td>$0.94</td>
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<tr>
<td>Energy Cost Contribution</td>
<td>$0.18</td>
<td>$0.00</td>
<td>$0.00</td>
<td>$0.18</td>
</tr>
<tr>
<td>Other Costs Contribution</td>
<td>$0.17</td>
<td>$1.05</td>
<td>$0.00</td>
<td>$1.22</td>
</tr>
<tr>
<td>Purchased Capital Cost ($k)</td>
<td>$42</td>
<td>$31</td>
<td>$26</td>
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<tr>
<td>Total Capital cost ($k)</td>
<td></td>
<td></td>
<td></td>
<td>$150</td>
</tr>
</tbody>
</table>
Current Urban Hydrogen Delivery Costs

Urban: 250k people, Plant 62 miles from city gate

Market Penetration (%) vs. $/kg H2 for different delivery methods:
- Pipeline
- Pipeline Fit
- Liq H2
- Liq H2 Fit
- GH2 Tube Trailer

City Gate Delivery Costs: 250k people, Plant 62 miles from city gate.
Urban Hydrogen Delivery Costs at Research Targets

Urban: 250k people, Plant 62 miles from city gate

$/kg H2

- Pipeline
- Pipeline Fit
- Liq H2
- Liq H2 Fit
- GH2 Tube Trailer
- GH2 Tube Trailer Fit

Market Penetration (%)
### Low Mkt Penetration

**Current Costs: Tube Trailer Pathway**

City: 1M People, Plant 62 Miles from the City

<table>
<thead>
<tr>
<th>Refueling Station Size (kg/day)</th>
<th>100</th>
<th>100</th>
<th>1500</th>
<th>1500</th>
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<tbody>
<tr>
<td>LDV Market Penetration (%)</td>
<td>2%</td>
<td>4%</td>
<td>2%</td>
<td>4%</td>
</tr>
<tr>
<td>City H2 Demand (kg/day)</td>
<td>8,200</td>
<td>16,400</td>
<td>8,200</td>
<td>16,400</td>
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<tr>
<td># of Stations</td>
<td>118</td>
<td>236</td>
<td>8</td>
<td>16</td>
</tr>
<tr>
<td>% of Existing Stations</td>
<td>32%</td>
<td>64%</td>
<td>2%</td>
<td>4%</td>
</tr>
<tr>
<td>Distance between Station (miles)</td>
<td>1.6</td>
<td>1.1</td>
<td>6.2</td>
<td>4.4</td>
</tr>
<tr>
<td>Total Delivery Cost ($/kg)</td>
<td>$7.40</td>
<td>$6.90</td>
<td>$4.90</td>
<td>$4.40</td>
</tr>
<tr>
<td>Cost Contributions ($/kg)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Terminal</td>
<td>$2.40</td>
<td>$1.90</td>
<td>$2.40</td>
<td>$1.90</td>
</tr>
<tr>
<td>Tube Trailer</td>
<td>$2.60</td>
<td>$2.60</td>
<td>$1.70</td>
<td>$1.70</td>
</tr>
<tr>
<td>Station</td>
<td>$2.40</td>
<td>$2.40</td>
<td>$0.80</td>
<td>$0.80</td>
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</tbody>
</table>
Improvements to Scenario Model

- Mixed delivery pathway (e.g., pipeline to GH2 terminal to HP Tube Trailer)
- Variable sized Forecourts (50-6,000 kg/day)
- Carriers
- Energy efficiencies and CO₂ emissions
- Mixed demands/markets
  - combining urban areas
  - combining urban areas with interstate demand
- Initial overbuilding of delivery infrastructure
Key Learnings/Challenges

• 70 MPa Refueling
  – Higher compression and storage costs/greater challenge to meet targets
  – May require cooling at the refueling station
• Other potential needs for cooling at refueling stations
  – Metal hydride on-board storage
  – Cryo-gas on board storage
• H2 Quality Requirements
  – Will polishing purification be needed?
  – Geologic storage contamination issues?

➢ All these issues can increase cost

• Can Carriers change the Delivery Paradigm?
Key Learnings/Challenges

• Low Mkt Pentration
  – Low volumes means much higher delivery costs
  – Distributed/City-Gate production could reduce costs significantly
  – Potential breakthroughs: higher H2 content tube trailers, liquefaction, carrier approach?

• Forecourt costs are significant and need to be reduced
  – Larger and fewer forecourts is very beneficial
  – Compression: reliability needs to be improved, capital cost needs to be reduced
  – Storage: Need a breakthrough

• Pipelines are the current low cost pathway for the long term, but:
  – Hydrogen embrittlement concerns
  – How to move to pipelines (at least transmission) earlier?
  – High H2 content tube trailers could be cost effective for distribution

• System storage needs drive costs up
  – Need to better understand storage needs and demand cycles
  – Geologic storage feasibility is critical

• Compression Costs need to be reduced
Additional Information

• FreedomCAR and Fuels Partnership Delivery Tech Team
  – Comprehensive Delivery Roadmap

• Websites
  – www.hydrogen.energy.gov
  – www.eere.energy.gov/hydrogenandfuelcells/
Back-Up slides
Gaseous Hydrogen Delivery Pathway

Centralized Production

H₂

Compressor

Transmission pipeline

Compressor

Geologic Storage

Compression

Terminal

Storage

Loading rack

Note 1: sensors for leak detection, purity, and flow rate will be required at multiple locations

Note 2: rail and barge transportation is possible for large volume shipments between central production and a terminal facility

Note 3: intermediate storage possible at a variety of locations

Fueling Station

Storage

Compressor

Dispenser

Loading rack
Liquefaction Distribution Pathway

- Gaseous H₂ Production
- Liquefaction
- Pump
- Terminal
  - Storage
  - Loading rack
- Truck
- Fueling Station
  - Storage
  - Pump
  - Vaporization
  - Compressed Gas Dispenser
  - Liquid Dispenser
Hydrogen Carrier Delivery Pathway

- Carrier Production
- Carrier Regeneration
- Energy & Raw Materials
- Hydrogen Production
- Carrier Present for All Options
- Carrier for Round Trip Options
- Carrier for On-Board Production
- H₂
Current Urban Hydrogen Delivery Costs

City: 250k people, Plant 100 km (62 miles) from city gate

- Pipeline Fit
- Liq H2 Fit
- GH2 Tube Trailer

$/kg H₂ vs Market Penetration (%)
Current Urban Hydrogen Delivery Costs

Urban: 250k people, Plant 62 miles from city gate

- Pipeline
- Pipeline Fit
- Liq H2
- Liq H2 Fit
- GH2 Tube Trailer

Market Penetration (%)

$/kg H2

0% 10% 20% 30% 40% 50% 60% 70% 80% 90% 100%

$0.0 $2.0 $4.0 $6.0 $8.0 $10.0 $12.0 $14.0 $16.0 $18.0 $20.0 $22.0 $24.0

$1.75 $2.10 $3.52 $2.89 $1.75

$1.75 $2.10 $3.52 $2.89 $1.75
Urban Hydrogen Delivery Costs at Research Targets

City: 250k people, Plant 100 km (62 miles) from city gate

Market Penetration (%)

$/kg H2

Pipeline Fit
Liq H2 Fit
GH2 Tube Trailer Fit

$0.0
$2.0
$4.0
$6.0
$8.0
$10.0
$12.0
$14.0

0% 20% 40% 60% 80% 100%
Rural Hydrogen Delivery Costs at Research Targets

Rural: 300 mile cross

$/kg H2

Pipeline
Pipeline Fit
Liq H2
Liq H2 Fit
GH2 Tube Trailer
GH2 Tube Trailer Fit

$1.58
$2.29
$1.64
$1.58

Market Penetration (%)

0% 20% 40% 60% 80% 100%
Current* Hydrogen Delivery Costs vs. Distance Between Plant and City

Urban city: 250k people, 50% Market Penetration

- Pipeline
- Liq H2
- GH2 Tube Trailer

Distance Between Plant and City (miles)

$/kg H2
## Delivery Targets

<table>
<thead>
<tr>
<th>Category</th>
<th>Units</th>
<th>2005 Status</th>
<th>2015</th>
<th>2017</th>
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<tbody>
<tr>
<td><strong>Pipelines</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transmission Capital</td>
<td>$/mile</td>
<td>$700</td>
<td>$490</td>
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<tr>
<td>Distribution Capital</td>
<td>$/mile</td>
<td>$320</td>
<td>$190</td>
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<tr>
<td>Reliability (Embrittlement)</td>
<td></td>
<td>Acceptable for current service</td>
<td>Acceptable for H2 as a major energy carrier</td>
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<tr>
<td><strong>Compression</strong></td>
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<td></td>
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<tr>
<td>Large: Reliability</td>
<td></td>
<td>Low</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td>Large: Capital Cost</td>
<td>$M (200k kg/day)</td>
<td>$15</td>
<td>$9</td>
<td></td>
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<tr>
<td>Forecourt: Reliability</td>
<td></td>
<td>Medium</td>
<td>High</td>
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<tr>
<td>Forecourt: Capital Cost</td>
<td>$/kg/hr</td>
<td>$4.60</td>
<td>$3</td>
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<tr>
<td>Forecourt Fill Pressure</td>
<td>psi</td>
<td>5,000</td>
<td>10,000</td>
<td></td>
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<tr>
<td><strong>Tube Trailer</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Delivery Capacity</td>
<td>kg of H2</td>
<td>280</td>
<td>1,100</td>
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<tr>
<td>Capital cost</td>
<td>$</td>
<td>$165,000</td>
<td>&lt;$300,000</td>
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<td><strong>Storage Tanks</strong></td>
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<tr>
<td>Capital Cost</td>
<td>$/kg of H2</td>
<td>$820</td>
<td>$300</td>
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<td><strong>Liquefaction</strong></td>
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<tr>
<td>Small: Capital Cost</td>
<td>$M (30,000 kg/d)</td>
<td>$60</td>
<td>$35</td>
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<tr>
<td>Small: Energy Efficiency</td>
<td>%</td>
<td>73%</td>
<td>84%</td>
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<tr>
<td>Large: Capital Cost</td>
<td>$M (300,000 kg/d)</td>
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<td>$120</td>
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<tr>
<td>Large: Energy Efficiency</td>
<td>%</td>
<td>80%</td>
<td>88%</td>
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<td><strong>Carriers</strong></td>
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<tr>
<td>Carrier H2 Content</td>
<td>% by weight</td>
<td>3%</td>
<td>13%</td>
<td></td>
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<tr>
<td>Carrier H2 Content</td>
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<td>Energy Efficiency</td>
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<td>System Cost Contribution</td>
<td>$/kg H2</td>
<td>Undefined</td>
<td>&lt;$1</td>
<td></td>
</tr>
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</table>
Liquid Carriers

- *Ethanol, Methanol, Bio-oils, Ammonia, etc.*

- **Liquid Hydrocarbons**: A liquid hydrocarbon is catalytically dehydrogenated at a station or on a vehicle and “dehydrided” is then returned to a central plant or terminal for rehydriding:

  \[ C_nH_{2n} \leftrightarrow C_nH_n + \frac{n}{2} H_2 \]
Carriers

**Solid Carriers**

- *Metal Hydrides*
- *Nanostructures:* Single-wall carbon nanotubes (SWNTs). Other Nanostructures

**Flowable Powders, Slurries, “Bricks”**: Stable solid carriers might be delivered in many different ways. Slurries have been mentioned, but novel systems such as flowable powders or solid “bricks” might also be potential delivery mechanisms.