Economic and Environmental Perspectives of Hydrogen Infrastructure Deployment Options

Amgad Elgowainy
Argonne National Laboratory

Presentation to NASEM Committee

June 26, 2019
Today, more than 10M metric tons of hydrogen are produced in the U.S. annually

1600 mi. of H₂ pipeline; 10 Liquefaction plants in North America

✔️ 4 planned liquefaction plants recently announced
Today, hydrogen cost at the dispenser in CA is $13-$16/kg

Bulk of H₂ cost is in delivery and refueling
Tecno-Economic Analysis (TEA) suite of models

https://hdsam.es.anl.gov/
Infrastructure of Gaseous Hydrogen Delivery

Centralized Gaseous $H_2$ Production

- Compressor
- Storage
- Loading Bays

Transmission Pipeline

- Compressor
- Geologic Storage

Gaseous Terminal

- Tube-Trailer
- Distribution Pipeline

Gaseous Terminal

Fueling Station

- Compressor
- Cascade
- Refrigeration
- Dispenser
- Storage
Infrastructure of Liquid Hydrogen Delivery

Centralized Gaseous H₂ Production

Liquefier

Fueling Station

Compressed Gas Dispenser

Cryogenic Storage

Loading Bays

Cryogenic Storage

Vaporizer

High-Pressure Cryo-Pump

Liquid Truck
Hydrogen Delivery Scenario Analysis Model (HDSAM)

Scenario Definition

Market
(all U.S. cities > 50K population)

Penetration

0 25 50 75 100

Delivery & Dispensing Mode

Financial/Economic Inputs and Assumptions

Delivery Cost
$/kg_{H2}

Capital

Operating

Energy

Station Cost
$/kg_{H2}

Compressor 45%

Dispenser 13%

Storage 20%

Refrigeration 12%

Controls/Other 9%

Electrical 3%


Costs of New Delivery & Dispensing for LDVs

Assuming current technology

- Trucking is lowest cost option with small market demand (near-term)
- Pipeline is lowest cost option with large market demand (long-term)

Production cost is additional

- Pipeline
- Liquid Tanker
- Tube Trailer
Hydrogen Refueling Station Models

Evaluate impacts of key market, technical, and economic parameters on refueling cost \([$/kg_{\text{H}_2}]\) of light-duty and heavy-duty fuel cell vehicles

HRSAM  HDRSAM

Available at: http://hdsam.es.anl.gov/
Cost Drivers of Hydrogen Fueling

Delivery:
- Compressor: 45%
- Storage: 20%
- Dispenser: 11%
- Refrigeration: 12%
- Electrical: 3%
- Controls/Other: 9%

Capital Costs of Hydrogen Fueling Stations
(Simulated, $1.5-$2M)

- Compressor: 45%
- Storage: 20%
- Dispenser: 11%
- Refrigeration: 12%
- Electrical: 3%
- Controls/Other: 9%

~200-300 kg/day HRS

700 bar
1.5 kg/min
Impact of station utilization and capacity on refueling station cost for FC LDVs

Today (low volume)  
Early market (12,000 FCEVs)  
300 kg/day station

Future (R&D and high volume)  
Mature market (120,000 FCEVs)  
1000 kg/day station

Production and delivery costs are additional

15-year Analysis Period
Impact of fueling rate on FC HDV refueling cost

- Faster fills require higher capacity equipment and result in higher cost
- Liquid stations can handle faster fills with less cost increase

Fleet Size: 30 buses
Fill Amount: 35 kg
350 bar, Type III tanks
Fill Strategy: Back-to-Back

Production and delivery costs are additional
Impact of HDV fleet size (demand) on refueling cost

- Fleet sizes have a strong impact: cost can drop to ~$1/kg_{H2} with large fleet size
- Liquid station, in general, provides a lower refueling cost option

**Graph:**

- **Gaseous Station:**
  - Fill Amount: 35 kg
  - Fill Rate: 3.6 kg/min
  - 350 bar, Type III tanks
  - Fill Strategy: Back-to-Back
  - Levelized Refueling Cost [\$/kg_{H2}]
    - 10: $6.00
    - 30: $5.00
    - 50: $3.00
    - 100: $1.00

- **Liquid Station:**
  - Levelized Refueling Cost [\$/kg_{H2}]
    - 10: $4.00
    - 30: $3.00
    - 50: $2.00
    - 100: $1.00

Production and delivery costs are additional.
The GREET® (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) Model

GREET 1 model:
Fuel-cycle (or well-to-wheels, WTW) modeling of vehicle/fuel systems

- Stochastic Simulation Tool
- Algae Process Description (APD)
- Carbon Calculator for Land Use Change from Biofuels (CCLUB)

GREET 2 model:
Vehicle-cycle modeling for light-duty vehicles

VEHICLE CYCLE (GREET 2 Series)

FUEL CYCLE (GREET 1 Series)

WELL TO PUMP

RECYCLING OF MATERIALS
Hydrogen production today is mainly from SMR, but other low-carbon pathways exist today.

At 72% NG to H₂ energy efficiency (LHV-basis)

Well-to-plant gate GHG emissions = 11 kg₃CO₂e/kg₇H₂

Note: Gasoline (E10) WTW GHG emissions also = 11 kg₃CO₂e/GGE
Energy Penalty and GHG Emissions are Critical for Environmental Impacts of Liquefaction

→ Liquefaction GHG emissions* = 0-7 kg$_{CO_2e}$/kg$_H_2$

*12 kWhe/kg$_H_2$

Four additional $H_2$ liquefaction plants have been recently announced to serve the growing market

<table>
<thead>
<tr>
<th>Region</th>
<th>Liquefaction Capacity (MT/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>California</td>
<td>30</td>
</tr>
<tr>
<td>Louisiana</td>
<td>70</td>
</tr>
<tr>
<td>Indiana</td>
<td>30</td>
</tr>
<tr>
<td>New York</td>
<td>40</td>
</tr>
<tr>
<td>Alabama</td>
<td>30</td>
</tr>
<tr>
<td>Ontario</td>
<td>30</td>
</tr>
<tr>
<td>Quebec</td>
<td>27</td>
</tr>
<tr>
<td>Tennessee</td>
<td>6</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>263</strong></td>
</tr>
</tbody>
</table>
Renewable sources are key for sustainable $H_2$ production

Assuming 26 mpg for gasoline ICEV and 55 mpgge for $H_2$ FCEV
Renewable $H_2$ roll out with public support is needed to overcome challenges of early markets

<table>
<thead>
<tr>
<th>Market Phase</th>
<th>Public Support?</th>
<th>Profitable?</th>
<th>Technology Reliable?</th>
<th>Sustainable?</th>
</tr>
</thead>
<tbody>
<tr>
<td>[1] Demonstration</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>[2] Early/Precommercial</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Pseudo Sustainable*</td>
</tr>
<tr>
<td>[3] Commercial</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Self Sustainable</td>
</tr>
</tbody>
</table>

* i.e., with public support
California LCFS can also generate credits for H₂ production and delivery pathways

- Hydrogen to be a mandatory reporting fuel
- LCFS credits recently trading near $200/MT
  - Can reduce H₂ cost by $2-$6/kg_H₂

1 kg_H₂ = 1 GGE

source: http://www.arb.ca.gov/fuels/lcfs/dashboard/dashboard.htm
Acknowledgment

The presented models and analysis have been supported by DOE’s Office of Energy Efficiency and Renewable Energy’s Fuel Cell Technologies Office over the past 15 years.
aelgowainy@anl.gov

Visit us at:

For Techno-Economic Analysis of hydrogen infrastructure:

https://hdsam.es.anl.gov/

For Environmental Life Cycle Analysis:

https://greet.es.anl.gov/