Fuel Cell Technologies Office Webinar

Manufacturing Competitiveness and Supply Chain Analyses for Hydrogen Refueling Stations

05/11/2017

Presenter: Ahmad Mayyas
Analyst - Clean Energy Systems
National Renewable Energy Laboratory
NREL/PR-6A20-68871
Question and Answer

- Please type your questions into the question box
Manufacturing Competitiveness and Supply Chain Analyses for Hydrogen Refueling Stations

Ahmad Mayyas
National Renewable Energy Laboratory
I. Introduction
II. International HRS Status
III. Analysis of HRS Capital Cost
IV. Manufacturing of HRS components
V. Concluding Remarks
Introduction
Relevance & Goals

• Provide a platform for manufacturing cost analysis for major hydrogen refueling station (HRS) systems
  – Identify cost drivers of major parts in the HRS
  – Investigate effect of *learning experience* and *availability of part suppliers* on the cost of some HRS systems

• Study supply chain and evaluate U.S. manufacturing competitiveness in the international market
Approach

Global Assumptions (e.g. capital, tool life, building life)

Local Assumptions by Country (e.g. labor, energy cost, building cost)

**Manufacturing Cost Model**
(compressor, storage tanks, dispenser, chiller, and heat exchanger)

**Minimum Sustainable Price**
(manufacturing cost, profit margin, transportation)

Compare to Other Cost Studies (HRSAM, H2FIRST, California, Japan, Europe)

Benchmark with Existing/Future Commercial Products

**Qualitative Factors**
(e.g. skilled labor, existing supply chain, regulations, tax policy)

**Quantifying These Factors**

**HRS Rollouts 2005-2016**
(PNNL, CEC, NEDO, HySUT, NOW, CEP)

**HRS Trade Flows**
(HRS developers, part suppliers)

**Supply Chain Maps**
HRS technology (gaseous, liquid, onsite) system components

**Future HRS Rollouts 2016-2030**

**Key Outputs**

1) HRS system manufacturing costs and minimum sustainable prices
2) International trade flows and supply chain maps (U.S. supply chain)
3) Estimation of future HRS technologies cost and effects on H₂ price
Hydrogen Delivery to the HRS

A configuration of a hydrogen station with gaseous hydrogen delivery

Truck delivery → Compressed H₂ → Tube storage → Compressor → High pressure hydrogen storage/cooling → Dispenser

A configuration of a hydrogen station with Liquid hydrogen delivery

Truck delivery → Liquid Hydrogen → Liquid H₂ Tank → Cryogenic Pump → Evaporator → Storage/ buffer tanks → Dispenser

A configuration of a hydrogen station with Liquid hydrogen delivery
Gaseous HRS Components

Hydrogen Refueling Station (HRS)

Compression System
- Bleed Valves
- Check Valves
- Air Operated Valves
- Position Switch
- Compressor
- Pressure Safety Valve
- Hydrogen Receiving

Storage System
- Compressor
- Check Valves
- Bleed Valves
- Pressure Safety Valve
- Bulk Pressure Storage
- Air Operated Valves
- Cascade Storage
- Pressure Safety Valve
- Tubing and Fittings

Dispensing System
- PLC (card reader, digital display, etc.)
- Nozzles (35MPa/70MPa)
- Valves
- Hoses
- Tubing
- Fittings
- Cooler
- Heat Exchanger
- PLC/Solenoid Valves
- Utility Feed
- Motors and Transmitters
- IR Flame Detectors

Modeled
FCEV Sales 2015-2030

- 2020 sales/production estimate >30,000 FCEVs
- 2030 sales/production estimates >250,000 FCEVs on roads
- Is hydrogen infrastructure ready to support this number of FCEVs?

CEMAC – Clean Energy Manufacturing Analysis Center
II International HRS Status
International HRS Rollouts

HRS: Hydrogen Refueling Station

Data Sources: PNNL, CEC, NEDO, HySUT, NOW, CEP

† Rollout in 2016 is based on the announced HRS
HRS Trade Flows Map

Data Sources: PNNL, CEC, HySUT, H2Stations.org
International Manufacturers

This map can be accessed from: https://maphub.net/mayyas111/HRS
III Analysis of HRS Capital Cost
HRS Capital Cost

**HRS Cost - Europe - Air Liquide Analysis**
- Labor and other expenses
- Piping + Control & safety
- Dispenser
- Storage tanks
- Electrical
- Chiller
- Compressor

Mossa, 2013

**HRS Cost - Japan**
- Labor and other expenses
- Piping + Control & safety
- Dispenser
- Storage tanks
- Electrical
- Chiller
- Compressor

Shinka, 2014
Suzauki, 2014

**HRS Cost - USA - ANL Analysis**
- Labor and other expenses
- Piping + Control & safety
- Dispenser
- Storage tanks
- Electrical
- Chiller
- Compressor

Elgowainy et al., 2015

**HRS Cost - USA - H2FIRST Analysis**
- Labor and other expenses
- Piping + Control & safety
- Dispenser
- Storage tanks
- Electrical
- Chiller
- Compressor

Pratt et al., 2015

**Liquid H₂ Stations**

Other Expenses include site engineering, permitting, commissioning, and construction

CEMAC – Clean Energy Manufacturing Analysis Center
IV Manufacturing of HRS components
Assumptions- Compressor Manufacturing

• 1 stage compressor
• Compression ratio < 6:1
• $P_{\text{in}} = 150$-$200$ bar, $P_{\text{out}} = 350$-$420$ bar (5,000-$6,000$ psi)
• Manufacturing cost model for compressor case and internal parts only
• Balance of system was added to the direct manufacturing cost of the compressor case & internal parts
• Profit margin was estimated using weighted average cost of capital (WACC) method
• 70 MPa HRS might need a hydrogen booster besides the compressor to increase the pressure from 350-420 bar (35-42 MPa) to about 700-900 bar for direct filling or storage in the cascade/buffer system
Process Flow Diagram - Piston Compressor
Manufacturing Cost Analysis

- Compressor frame and internal parts
- Not including balance of system
H₂ Compressor - Balance of System
Minimum Sustainable Price - Compressor

- Compressor capacity = 92 Nm³/hr or 200 kg/day (1 stage)
- $P_{in} = 150-200$ bar, $P_{out} = 350-420$ bar
- Shipping cost is assumed for shipping compressors from East Coast to West Coast in this example
- Margin was calculated using WACC
Sensitivity Analysis

Input parameters were varied by +/- 10% (relative) from base values to identify the modeled price sensitivities to various input assumptions.
Minimum Sustainable Price - Compressor

- United States advantages are lower shipping and interest rates and longer experience in this field
- China’s advantage relative to the U.S. is driven by lower labor (including assembly), low material cost, building and energy costs
- Mexico’s advantage relative to the U.S. is driven by lower labor (including assembly), and building costs
Hydrogen Dispenser

- Connector (Fujikin)
- Manual valve (Fujikin)
- Pressure Gauge (Nagano Keiki)
- Check valve (WEH)
- Flowmeter (OVAL)
- Breakaway coupling (Nitto Kohki)
- Control valve (Fujikin)
- Control valve (Fujikin)
- Flexible hose (Osaka Rasenkan)
- Dispenser (Tatsuno)
- Fuel filling nozzle (WEH)
Dispenser Cost Analysis

H35 Dispenser Parts Cost=$35,048

- Hydrogen filter 2%
- Enclosure 3%
- Electrical & Control 9%
- Sensors (Pressure, Temp., H2 leak) 12%
- Nozzle & Hose 13%
- Valves and Meters 57%
- Piping and Tubing 3%
- Other 1%

H35/H70 Dispenser Parts Cost=$67,595

- Hydrogen filter 2%
- Enclosure 1%
- Electrical & Control 5%
- Sensors (Pressure, Temp., H2 leak) 7%
- Nozzle & Hose 22%
- Valves and Meters 60%
- Piping and Tubing 2%
- Other 0%

Parts & Assembly Cost (assuming 20% discount per 10X increase in purchased quantity)

H35 Dispenser Cost

H35/H70 Dispenser Cost
Minimum Sustainable Price - Dispenser

- United States advantages are lower shipping and interest rates and longer experience in this field
- Mexico’s advantage relative to the U.S. is driven by lower labor, and building costs
Advance Heat Exchanging Technology

DCHE: Diffusion Bonded Compact Heat Exchanger

Images for: NREL HRS and Kobelco DCHE

Example of integration with dispenser

Photo Credit: JX Nippon Oil & Energy Co.

HySUT
Ebina Chuo Hydrogen Station
Microchannel Heat Exchanger - Process Flow

- Plate cleaning
- Chemical etching
- Quality check (profilometer)
- Mask (Ferric Chloride)
- Cold & Hot plate stacking
- Vacuum diffusion bonding
- Welding nozzles to the stack
- Adding housing
- Pressure testing

- Chemical etching can be replaced by laser grooving.
- Laser grooving speed= 300mm/min

Image Source: Heatric.com
Plate Design Parameters

Parabolic Channels

\[ y = h \left(1 - \frac{x^2}{a^2}\right) \]

Square Channels

<table>
<thead>
<tr>
<th>Plate width (mm)</th>
<th>300 mm</th>
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<tr>
<td>Plate length (mm)</td>
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<table>
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<th>a (mm)</th>
<th>h (mm)</th>
<th>Arc Length (mm)</th>
<th>Plate Thickness (mm)</th>
<th>Transfer Area of Individual Channel (mm²)</th>
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<th>Plate Thickness (mm)</th>
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<td>400.00</td>
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</table>

*Individual Plate Size = 400*300 mm² = 375,000 mm²*
*Distance between Individual Channels = 750 μm*
- United States advantages are lower shipping and interest rates and longer experience in this field
- Mexico’s advantage relative to the U.S. is driven by lower labor, and building costs
- China’s advantage relative to the U.S. is driven by lower labor, low material cost, building and energy costs
Concluding Remarks
HRS Capital Cost and Hydrogen Price

Ways of reducing hydrogen cost

- Economies of scale for HRS systems can reduce hydrogen cost more than 5-10% (~20 of CSD cost)
- Standardization can do similar thing (e.g. compressors, chillers, heat exchangers, etc.)
- Installing liquid hydrogen station. Depends on number of FCEV and utilizations of HRS
Conclusions

• Lack of standardization may result in higher manufacturing cost

• U.S.-based manufacturers have advantages of longer experience in the field and low energy cost

• Future technologies and economies of scale will have great impact on the HRS cost and H₂ prices
Thank you

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Question and Answer

- Please type your questions into the question box
Thank you

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Ahmad Mayyas  
(Ahmad.Mayyas@nrel.gov)

hydrogenandfuelcells.energy.gov


References

- Amgad Elgowainy et al., 2015. Overview of Station Analysis Tools Developed in Support of H2USA http://energy.gov/sites/prod/files/2015/05/f22/Fcto_webinarslides_h2usa_station_analysis_tools_051215.pdf
- UKH2Mobility. http://www.theregister.co.uk/2013/02/04/hydrogen_could_be_mainstream_car_fuel_by_2030/
- http://autogreenmag.com/tag/india/page/6/
- Bruce Hedman and Ken Darrow. CHP Technology Characterizations. July 2010
Backup Slides
## Dispenser Cost Analysis

### Single Hose Dispenser H35

<table>
<thead>
<tr>
<th>Part No.</th>
<th>Part</th>
<th>Supplier 1</th>
<th>Required Units</th>
<th>Dispenser ($)</th>
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<td>7</td>
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<td>Hydrogen filter</td>
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### Dual Hose Dispenser H35/H70

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<td><strong>Total</strong></td>
<td></td>
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<td><strong>67,595</strong></td>
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</table>
Double Tube Heat Exchanger

HX Design

Counter Flow

H₂ out

1.000 mm

Coolant in

150 mm

Coolant in

H₂ out

Outer Tube
Stainless Steel 316L
D_out = 1”
D_in = ¾”
Wall Thickness = 0.125”

Inner Tube
Stainless Steel 316L
Pressure Rating = 20,000 psi (1378 bar)
D_out = ½”
D_in = 0.124”
Wall Thickness = 0.188”

Process Flow

Tube inspection → CNC bending → Quality checking → Adding spacer to internal tubes → Tube welding

Pressure testing → Housing/closure → Welding nozzle → Stacking and insulation
MSP for Double Tube Heat Exchanger (17 kW)

MSP for Double Tube Heat Exchanger (34 kW)