Manufacturing Competitiveness Analysis for Hydrogen Refueling Stations

Department of Energy Annual Merit Review for Fuel Cell Research

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Overview

Timeline
• Project start date: April 2015
• Project end date: Dec. 2016
• Percent complete: 75%

Technical Barriers
• A: Lack of hydrogen/carrier and infrastructure options analysis
• B: Reliability and costs of gaseous hydrogen compression
• E: Gaseous Hydrogen Storage and Tube Trailer Delivery Costs

Budget
• Total project funding
  – DOE share: $0.4M
  – Contractor share: n.a.
• Funding received in FY15: $400k
• Planned Funding for FY16: Pending

Collaborators
• Sandia National Labs
• Argonne National Lab
• Pacific Northwest National Lab
• Other Industry Advisors and Experts
The Clean Energy Manufacturing Analysis Center (CEMAC) provides unique and high-impact analysis, benchmarking, and insights of supply chains and manufacturing for clean energy technologies that can be leveraged by decision makers to inform research and development strategies, and other policy and investment decisions. Housed at the National Renewable Energy Laboratory and operated by the Joint Institute for Strategic Energy Analysis, CEMAC engages the DOE national lab complex, DOE offices, U.S. federal agencies, universities, and industry to promote economic growth and competitiveness in the transition to a clean energy economy.

CEMAC was established in 2015 by the U.S. DOE’s Clean Energy Manufacturing Initiative.
Relevance & Goals

• Provide a platform for manufacturing cost analysis for major hydrogen refueling station (HRS) systems
  – Identify cost drivers of hydrogen compressor (40-60% of total HRS capital cost)
  – Identify cost drivers of various storage tank technologies and configurations
  – Investigate effect of learning experience and availability of part suppliers on the chiller, heat exchanger and dispenser costs

• Work with FCTO in establishing manufacturing cost models for HRS’s
  – Establish a manufacturing cost framework to study cost of HRS systems (compressor, storage tanks, chiller & heat exchanger, and dispenser)
  – Assist in highlighting potential cost reductions in manufacturing phase for future R&D projects in this field
**Approach**

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

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

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**Manufacturing Cost Model**
(compressor; storage tanks; dispenser; chiller, etc.)

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**Minimum Sustainable Price**
(Mnf’g cost, profit margin, transportation, etc.)

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

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**Quantifying these factors**

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**Compare to other cost studies**
(HRSAM; H2FIRST; California; Japan, Europe)

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**Benchmark with Existing/Future Commercial Products**

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**HRS Rollouts 2005-2016**
(PNNL; CEC; NEDO; HySTU, NOW; CPE etc.)

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

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**Supply Chain Maps**
HRS technology (Gaseous, Liquid, Onsite) System components

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**Future HRS Rollouts 2016-2030**

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**Key Outputs**

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

A configuration of a hydrogen station with gaseous hydrogen delivery:
- Truck delivery
- Compressed $\text{H}_2$
- Tube storage
- Compressor
- High pressure hydrogen storage/cooling
- Dispenser

A configuration of a hydrogen station with liquid hydrogen delivery:
- Truck delivery
- Liquid Hydrogen
- Liquid $\text{H}_2$ Tank
- Cryogenic Pump
- Evaporator
- Dispenser
Accomplishments: International HRS Rollouts

2015/2016 ➞ 51 HRS†
2020 ➞ 87 HRS
2030 ➞ >500 HRS

2015/2016 ➞ ~15 HRS†
2020 ➞ 65 HRS
2030 ➞ 330 HRS

2015/2016 ➞ 50 HRS†
2020 ➞ 300 HRS
2030 ➞ 1,000 HRS

2015/2016 ➞ 43 HRS†
2020 ➞ 168 HRS
2030 ➞ 500 HRS

2015/2016 ➞ 100 HRS†
2020 ➞ 187 HRS
2030 ➞ >500 HRS

† Rollout in 2015/2016 is based on the announced number of HRS’s

HRS: Hydrogen Refueling Station
Accomplishments: HRS Trade Flows Map

- HRS’s trade flow by number of stations in the past 11 years
- Germany is leading European countries in the numbers of produced HRS’s and the number of installations (~100 HRS’s)
- Japan has a strategic plan for Hydrogen infrastructure (~100 HRS’s by end of FY 2015; about 87 already installed)
Accomplishments: HRS Flow Map

HRS’s by Capacity; medium to high capacities (>50 kg/day)

International HRS’s including planned HRS’s be end of 2016
Accomplishments: HRS Capital Cost

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

Pratt et al., 2015
Accomplishments: Estimated Capital Cost Using Regression Analysis

Regression Analysis Results

- **Example 1: 100 kg/day HRS:**
  - Regression analysis: $1.30M in Europe; $1.95M in Japan; **$0.78M in USA**
  - HDSAM/ANL estimate: $<0.85M ($2015)
  - H2FIRST estimate: $0.97M ($2014)
  - **CEC actual (130 kg/day): $1.61M ($’14-’15)**

- **Example 2: 200 kg/day HRS:**
  - Regression analysis: $1.5M in Europe; $2.24M in Japan; **$0.96M in USA**
  - H2FIRST estimate: $0.91M ($2014)
  - **CEC actual (180 kg/day): $1.98M ($’14-’15)**

Other Expenses include site engineering; permitting; commissioning; and construction.
Assumptions- Compressor Manufacturing

- 1 stage compressor
- Compression ratio < 6
- $P_{\text{in}} = 150-200 \text{ bar} \; ; \; P_{\text{out}} = 350-420 \text{ bar} \; (5,000-6,000 \text{ psi})$
- 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
- 30% of the direct manufacturing cost was added as a profit margin (average value for machinery and equipment in early markets)
- 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
Accomplishment: Manufacturing Cost Analysis - Hydrogen Compressor

While diaphragm compressors have maintenance and performance advantages over piston compressors, they are also considerably more expensive.*

Process Flow - Piston Compressor - 1 stage

- Crank case
- Casting (Cast iron; ASTM class 40 or 50)
- Crank shaft
- Cleaning
- Machining
- Forging (Carbon steel ASTM 1020)
- Bearings
- Sheet Forming (Carbon steel ASTM 1020)
- Connecting Rod
- Cleaning
- Machining
- Forging (Carbon steel ASTM 1020)
- Crosshead
- Casting (Cast iron; ASTM class 40 or 50)
- Cylinder
- Cleaning
- Machining
- Forging (Carbon steel ASTM 1020)
- Liner
- Cleaning
- Machining
- Forging (Carbon steel ASTM 1020)
- Piston
- Casting (Cast iron; ASTM class 40)
- Piston Rod
- Hardening
- Cleaning
- Machining
- Valley Seat & Guard
- Cleaning
- Machining
- Spring
- Forging (Low carbon steels; AISI 1037)
- Valve Poppets
- Cleaning
- Machining

Assembly -> Testing

Manufacturing Cost Breakdown (92 Nm³/hr @ 10 units/yr)
- Building 30%
- Labor 1%
- Energy 3%
- Capital 66%
- Variable 3%

Manufacturing Cost Breakdown (92 Nm³/hr @ 500 units/yr)
- Building 11%
- Labor 38%
- Energy 3%
- Capital 35%
- Variable 2%

While diaphragm compressors have maintenance and performance advantages over piston compressors, they are also considerably more expensive.*

Mfg cost = $28,450

Mfg cost = $5,150
Accomplishment: Sensitivity Analysis - H₂ Compressor Housing and Internal Parts

- **U.S. plant**→ Yield, capital, labor and material costs play major role in determining compressor manufacturing cost.
- **China plant**→ Yield, capital, and material costs play major role in determining compressor manufacturing cost.
- **U.S. manufacturers** have advantage of longer experience in hydrogen industry (compressors, dispensers, tanks, etc.)
- **Learning curve** is another qualitative factor that gives another advantage to U.S. manufacturers
Accomplishment: Compressor Balance of System Cost Analysis

- Motor cost estimated based on price of commercial industrial motors
- Control Unit shares about 59% of the total BOS parts cost.
- Total BOS cost = $21,076
- Discounts for high quantities can reduce BOS cost
- Assembly cost in U.S. plant = $7,100 (~300 man-hour; Avg. wages $23.63/hr)

<table>
<thead>
<tr>
<th>Part</th>
<th>Vendor 1</th>
<th>Description</th>
<th>Price ($)</th>
<th>Units</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor</td>
<td>Many vendors</td>
<td>Industrial motors for compressors</td>
<td>2,334</td>
<td>per unit</td>
<td>Avg. price for industrial motors</td>
</tr>
<tr>
<td>Pressure checking/Regulating Valves</td>
<td>AirGas Victor SR600-350-680 Heavy Duty High Pressure</td>
<td>Maximum inlet pressure of 5500 PSIG features die-forged brass body and spring housing cap for strength &amp; durability</td>
<td>802</td>
<td>per unit</td>
<td></td>
</tr>
<tr>
<td>Piping</td>
<td>Many vendors</td>
<td>ASTM A269; 8mm ID; 12 mm OD; 2 m length pipes; wall thickness=2mm; max</td>
<td>25</td>
<td>per meter</td>
<td>about 60-70 m required</td>
</tr>
<tr>
<td>Tubing and Fittings</td>
<td>Swagelok</td>
<td>Different fittings</td>
<td>44</td>
<td>per unit</td>
<td>24-64 per fitting</td>
</tr>
<tr>
<td>Pressure Relief Valve</td>
<td>High Pressure Equipment Company</td>
<td>Relief valves are offered in pressure ranges: 1,500 through 60,000 psi.</td>
<td>658</td>
<td>per unit</td>
<td></td>
</tr>
<tr>
<td>Air Actuated valve</td>
<td>n/a</td>
<td>used in PDC compressor</td>
<td>600</td>
<td>per unit</td>
<td></td>
</tr>
<tr>
<td>Oil filter &amp; Gauge</td>
<td>Zoro</td>
<td>HPOP PRESSURE, 0-4K PSI, GS</td>
<td>250</td>
<td>per unit</td>
<td>$217 Gauge; $32.74 filter</td>
</tr>
<tr>
<td>Oil Relief Valve</td>
<td>StarVal</td>
<td>RVH-05i; Stainless Steel Inline Pressure Relief Valve</td>
<td>729</td>
<td>per unit</td>
<td></td>
</tr>
<tr>
<td>Coolant Pump</td>
<td>AMT</td>
<td>Heavy Duty Industrial Coolant Pump</td>
<td>515</td>
<td>per unit</td>
<td></td>
</tr>
<tr>
<td>Control Unit</td>
<td>Allen Bradely</td>
<td>PLC + Operator Interface; Data Logging</td>
<td>13,000</td>
<td>per unit</td>
<td>Based on H2 compressor manufacturer comment</td>
</tr>
<tr>
<td>Other parts+skid</td>
<td>Local Suppliers</td>
<td>Other parts+skid</td>
<td>1,000</td>
<td>per unit</td>
<td></td>
</tr>
</tbody>
</table>
Accomplishment: Hydrogen Compressor - Minimum Sustainable Price

- 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 is assumed to be 30% of the manufacturing cost

Cost Breakdown:

- **Mfg cost = $80,268**

Cost Breakdown for 10 units/yr:

- Shipping: 1%
- Materials: 1%
- Labor: 3%
- Margin: 23%
- Assembly: 14%
- Building: 9%
- Balance of System: 27%
- Capital: 21%
- Variable: 1%

Cost Breakdown for 500 units/yr:

- Shipping: 2%
- Materials: 2%
- Labor: 8%
- Margin: 23%
- Assembly: 16%
- Building: 1%
- Balance of System: 48%
Accomplishment: Minimum Sustainable Price

- 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, low material cost, building and energy costs
- Mexico’s advantage relative to the U.S. is driven by lower labor, and building costs
Accomplishment: Seamless Metal H₂ Vessels (Type I)

Process Flow- Type 1 Steel Tanks

Steel Pipe Inspection → Ultrasonic Examination → Interior Grinding and Cleaning → Saw Cutting → CNC Spin Forging → Heat Treatment

Coating & Finishing → Blasting & Cleaning → Hydrostatic Testing → CNC Tube Threading → Non-Destructive Testing → Liquid Quenching

34CrMo4 Steel

Manufacturing Cost Curve (U.S. Plant)

Minimum Sustainable Price

MSP- 34CrMo4 Steel Tank (Storage Capacity= 25 kg H₂@380 Bar)

Profit margin=10% of total manufacturing cost
Remaining Challenges and Barriers

Challenges we’re seeking to overcome to improve the robustness of our study:

• Limited data on HRS component suppliers for international HRS’s
• Lack of competition between part suppliers (e.g. nozzles and hoses) make it hard to study potentials for cost reductions
• Finding collaborators in Europe and Asia is still a big challenge for our team
• Japan is updating its safety and standards, so it’s not clear how this will affect the cost of HRS’s
Proposed Future Work

- Develop new set of trade flow maps with flows by HRS developer and by component manufacturers
- Complete manufacturing cost analysis for other HRS’s systems (e.g. dispenser, heat exchanger and chiller)
- Study effect of standardization in several countries on the cost of HRS’s
- Study effect of future technologies and economies of scale on the HRS cost and hydrogen prices
Responses to 2015 AMR Reviewer Comments

• This is a new project and was not reviewed last year
Collaborations

• Joe Pratt: Sandia National Labs
  – Provided some cost data for manufacturing cost analysis
• Amgad Elgowainy & Marianne Mintz; Argonne National Lab (ANL)
  – Help in validating manufacturing cost model results & effect of qualitative factors (e.g. number of jobs created)
• Daryl Brown; Pacific Northwest National Lab (PNNL)
  – Provided data on HRS capital costs (HRSAM)
• Tetsufumi Ikeda; HySTU program; Japan
  – HRS installations in Japan
• Kareem Afzal and Osama Al-Qasem; PDC Machines
  – Provided critical inputs for manufacturing cost analysis for compressors
• Tetsuya Tanaka; Hitachi compressors, Japan
  – Provided some specifications for H2 compressors for Japanese market
• Sean Shunsuke Chigusa; Kobelco Compressors, Japan/USA
  – Provided some inputs for hydrogen compressor
• Flex Happe; Commercial Specialist at US consulate in Berlin, Germany
  – Provided some data about hydrogen station installations in Europe
• Industry stakeholders: provided estimates for dispenser cost (SunDyne, Tescom, Swagelok, HyDAC, High Pressure Equipment, Rust Automation & Control, SBS, MyDax, Welcon, Russels Technical, Thermofin, etc.)
Project Summary

- **Relevance**: Provide framework for manufacturing cost and supply chain analyses for hydrogen refueling stations
- **Approach**: Bottom-up cost analysis cost models; detailed supply chain maps and investigation of qualitative factors effect on manufacturing competitiveness
- **Technical Accomplishments and Progress**:  
  - Manufacturing cost models for hydrogen compressors, storage tanks and dispensers  
  - Statistical models to estimate HRS capital cost in USA, Germany and Japan  
  - Trade flow maps for global HRS’s
- **Collaboration**: Sandia; ANL and PNNL
- **Proposed Next-Year Research**:  
  - Complete manufacturing cost models for dispensers, heat exchangers and chillers  
  - Update supply chain maps with more emphasis on HRS parts/systems  
  - Investigate effect of qualitative factors in manufacturing competitiveness
Technology Transfer Activities

• Not applicable for this cost analysis
Thank you

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Backup Slides
Approach: Gaseous HRS Components

Hydrogen Refueling Station (HRS)

Compression System
- Bleed Valves
- Check Valves
- Air Operated Valves
- Position Switch
- Hydrogen Receiving Port
- Compressor
- Pressure Transmitter
- Check Valves
- Bleed Valves
- Air Dryer
- Hydrogen Filter

Storage System
- Low Pressure Storage
- Air Operated Valves
- Cascade Storage
- Tubing
- Fittings

Dispensing System
- Dispenser (card reader, digital display, etc.)
- Nozzles (35MPa/70MPa)
- Valves
- Hoses
- Tubing
- Fittings
- Chiller
- Heat Exchanger

Electrical System
- PLC/Gas Control Cabinet
- Wiring
- IR Flame Detectors
Accomplishments: HRS Flow Map

Number of HRS’s; medium to high capacities (>50 kg/day)

International HRS’s including planned HRS’s be end of 2016
Compressor Motor Cost Analysis

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>kg/day</th>
<th>Nm3/hr</th>
<th>Horse Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDC Machines</td>
<td>431.4</td>
<td>200.0</td>
<td>120</td>
</tr>
<tr>
<td>PDC Machines</td>
<td>10.8</td>
<td>5.0</td>
<td>5</td>
</tr>
<tr>
<td>Hofer</td>
<td>647.1</td>
<td>300.0</td>
<td>50</td>
</tr>
<tr>
<td>Hofer</td>
<td>1186.4</td>
<td>550.0</td>
<td>70</td>
</tr>
<tr>
<td>Hofer</td>
<td>1078.6</td>
<td>500.0</td>
<td>120</td>
</tr>
<tr>
<td>Haskel</td>
<td>540.6</td>
<td>250.6</td>
<td>28.5</td>
</tr>
<tr>
<td>Haskel</td>
<td>150.0</td>
<td>69.6</td>
<td>16.9</td>
</tr>
<tr>
<td>Haskel</td>
<td>200.7</td>
<td>93.1</td>
<td>27.4</td>
</tr>
<tr>
<td>Haskel</td>
<td>926.8</td>
<td>429.7</td>
<td>27.2</td>
</tr>
<tr>
<td>Haskel</td>
<td>127.2</td>
<td>59.0</td>
<td>19.3</td>
</tr>
<tr>
<td>Haskel</td>
<td>168.1</td>
<td>77.9</td>
<td>24</td>
</tr>
<tr>
<td>Haskel</td>
<td>266.4</td>
<td>123.5</td>
<td>27.2</td>
</tr>
<tr>
<td>Haskel</td>
<td>440.3</td>
<td>204.1</td>
<td>27.2</td>
</tr>
</tbody>
</table>

HRS capacity (Nm3/hr) Power (hp) Motor Price ($)  

| 50  | 17.83 | 1,939 |
| 75  | 22.39 | 2,334 |
| 100 | 26.33 | 2,675 |
| 150 | 33.07 | 3,259 |
| 200 | 38.87 | 3,762 |
| 300 | 48.83 | 4,624 |
| 400 | 57.40 | 5,367 |
| 500 | 65.08 | 6,032 |
Welded Metal $H_2$ Vessels (Type I)

Process Flow - Type 1 Steel Tanks

1. Blanking
2. Edge Preparation
3. Vessel Body Rolling
4. Welding
5. Heat Treatment
6. Head Cutting
7. Coating & Finishing
8. Blasting & Cleaning
9. Hydrostatic Testing
10. Welding Head to Vessel Body
11. Head Drawing

Manufacturing Cost Curve (U.S. Plant)

Cost Breakdown

Profit margin = 10% of total manufacturing cost
Elements of Manufacturing Analysis

- Innovation potential
- Manufacturing experience: *Learn by Doing*
- Intellectual property
- Cost of energy
- Cost of manufacturing
- Availability of investment capital
- Low-cost labor requirements & availability
- Product quality
- Skilled labor requirements & availability
- Tax policy
- Currency fluctuations
- Import and export policies
- Automation/advanced manufacturing
- Raw material availability
- Ease of transportation
- Existing supply chains
- Synergistic industries and clustering
- Existing or growing market
- Ease of doing business
- Safety
- Regulations
- Inventory costs and supply chain delays