CEMAC
Clean Energy Manufacturing Analysis Center

# Manufacturing Competitiveness Analysis for Hydrogen Refueling Stations

Department of Energy Annual Merit Review for Fuel Cell Research

*June 06, 2017 || Washington, D.C.*

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National Renewable Energy Laboratory

Project ID # MN017

# Overview

## Timeline

- Project start date: April 2015
- Project end date:  March 2018
- 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: $719 K
  - Contractor share: n.a.
- Funding received in FY16: $519 K
- Planned Funding for FY17: $0

## Collaborators

- Argonne National Laboratory
- Sandia National Laboratories
- Pacific Northwest National Laboratory
- Other Industry Advisors and Experts

# CEMAC Methodology & Key Results

| Type of Analysis | Method & Approach | Key Result |
|---|---|---|
| Global supply chain analysis | Define supply chain<br>Define mfrs<br>Evaluate market | Raw materials, Production & capacity by mfr and location |
| Bottom-up comparative cost analysis | Cost and value of mfg'd components along supply chain | Cost of mf'g in different locations, by cost category (e.g., labor, capital) |
| Location & scenario analysis | Impact of factors other than cost on location decisions; dynamic site-selection | Examples: labor availability, reliability of grid, currency, quality |
| **Technology Analysis** | Cost-benefit analysis of proposed technology performance and manufacturing process improvements | Rigorous method to compare technology development pathways<br>Identification and prioritization of R&D areas based on cost and technology impacts |

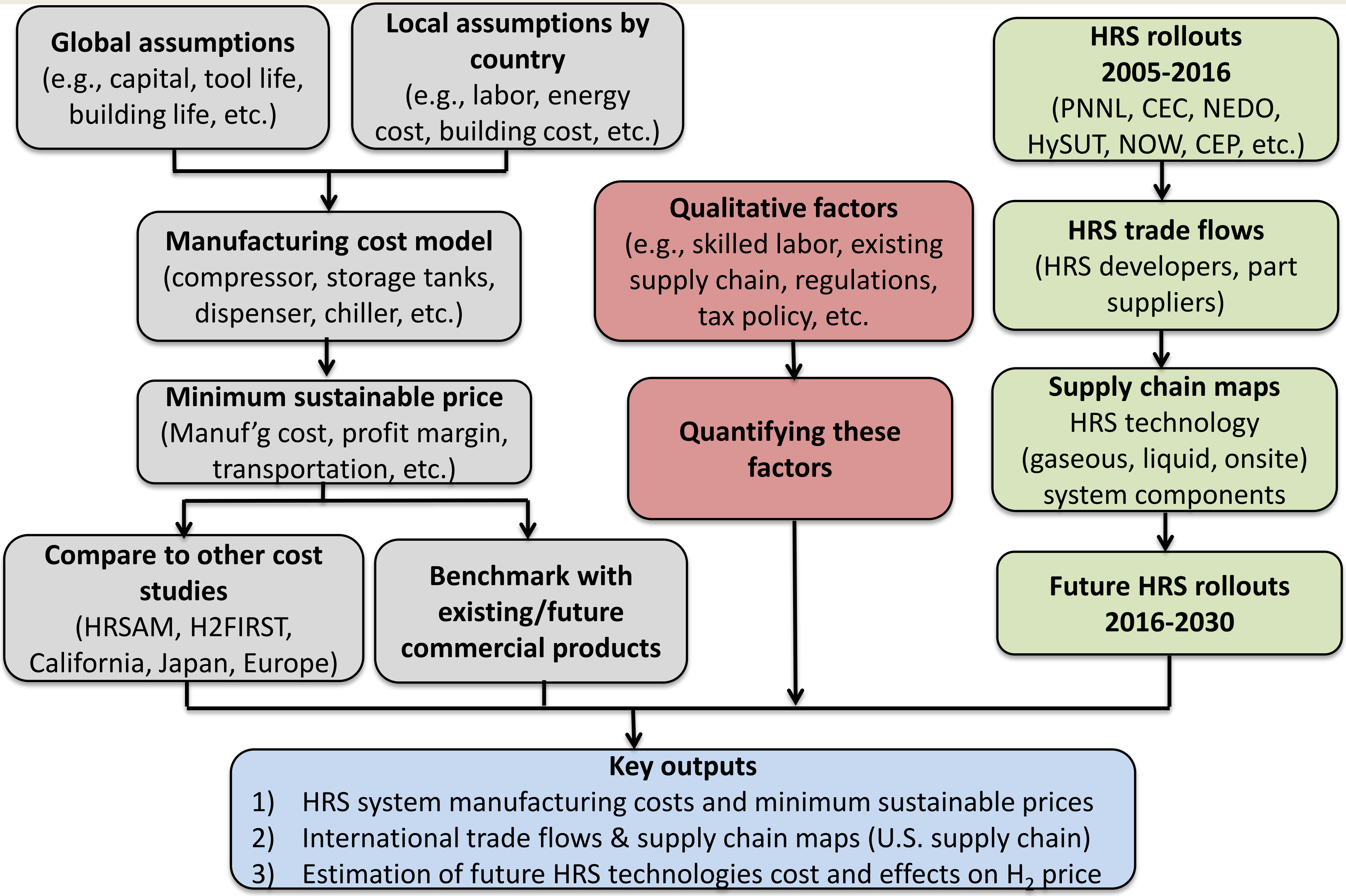
Sensitivity Analysis

Technology Manufacturing Roadmaps

# 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 to establish manufacturing cost models for HRSs
  - Establish a manufacturing cost framework to study cost of HRS systems (compressor, storage tanks, chiller & heat exchanger, and dispenser)
  - Highlight potential cost reductions in manufacturing phase for future R&D projects

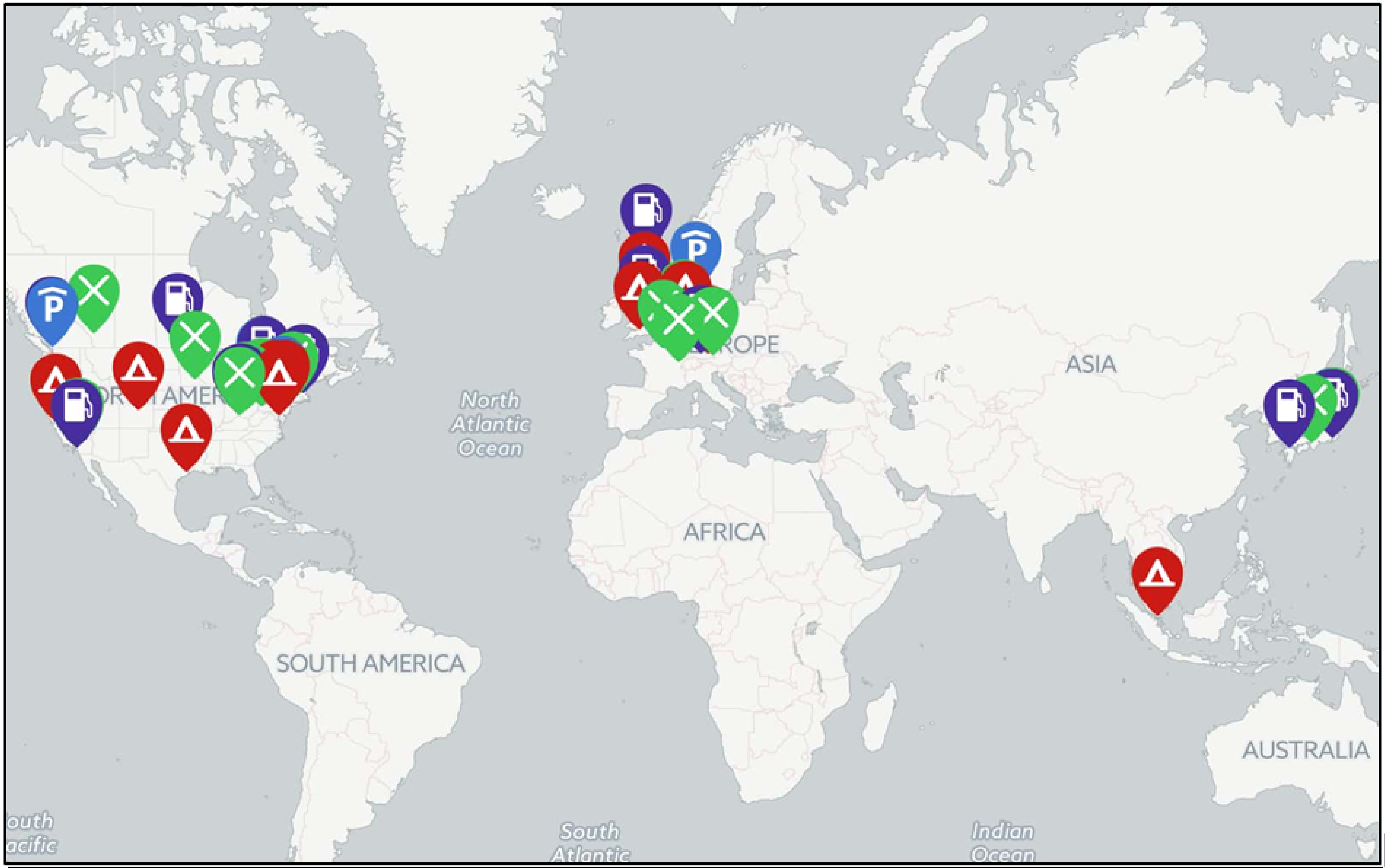
# Approach



Global assumptions
(e.g., capital, tool life, building life, etc.)
Local assumptions by country
(e.g., labor, energy cost, building cost, etc.)
Manufacturing cost model
(compressor, storage tanks, dispenser, chiller, etc.)
Minimum sustainable price
(Manuf'g cost, profit margin, transportation, etc.)
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, etc.
Quantifying these factors
HRS rollouts 2005-2016
(PNNL, CEC, NEDO, HySUT, NOW, CEP, etc.)
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 & supply chain maps (U.S. supply chain)
3) Estimation of future HRS technologies cost and effects on $H_2$ price

Accomplishment and Progress

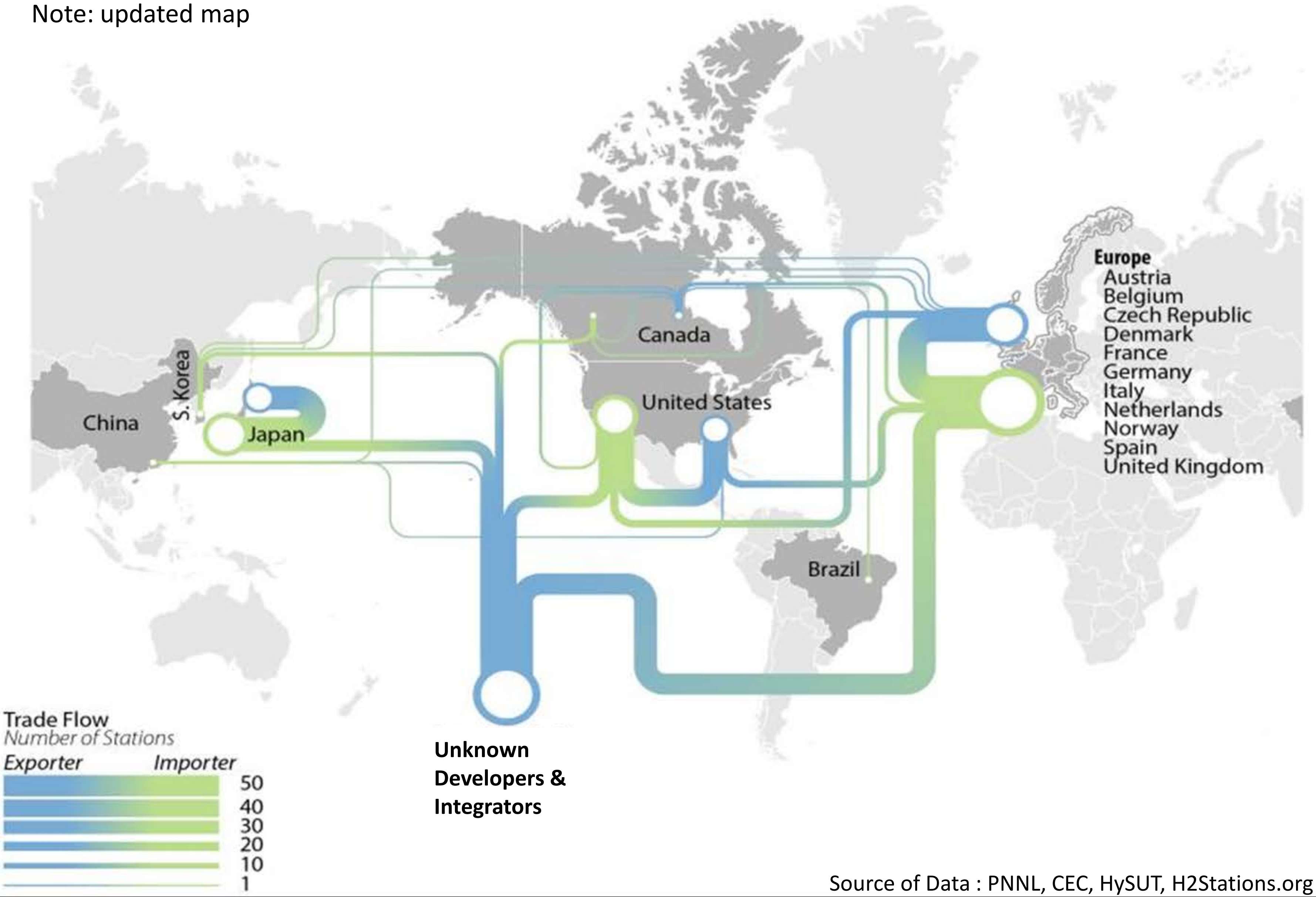
# International Manufacturers




| HRS Provider | Pressure Vessels Manufacturer | Compressor Manufacturer | Dispenser Manufacturer |
|---|---|---|---|

# HRS International Trade Flows Map

Note: updated map

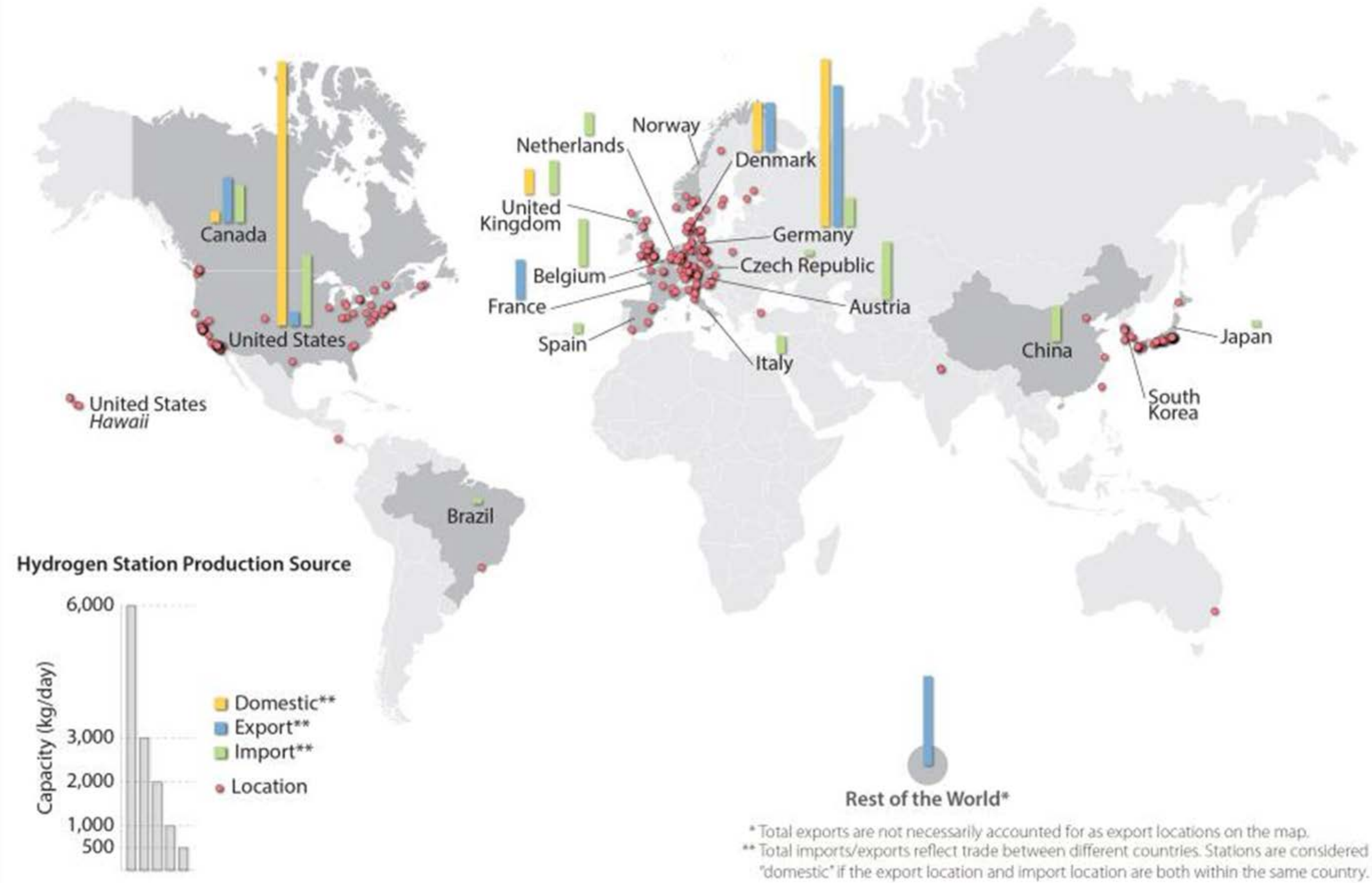



Source of Data : PNNL, CEC, HySUT, H2Stations.org

Accomplishment and Progress

# HRS Trade Flows Map

Note: updated map




Source of Data : PNNL, CEC, HySUT, H2Stations.org

Accomplishment and Progress

# Dispenser Cost Analysis

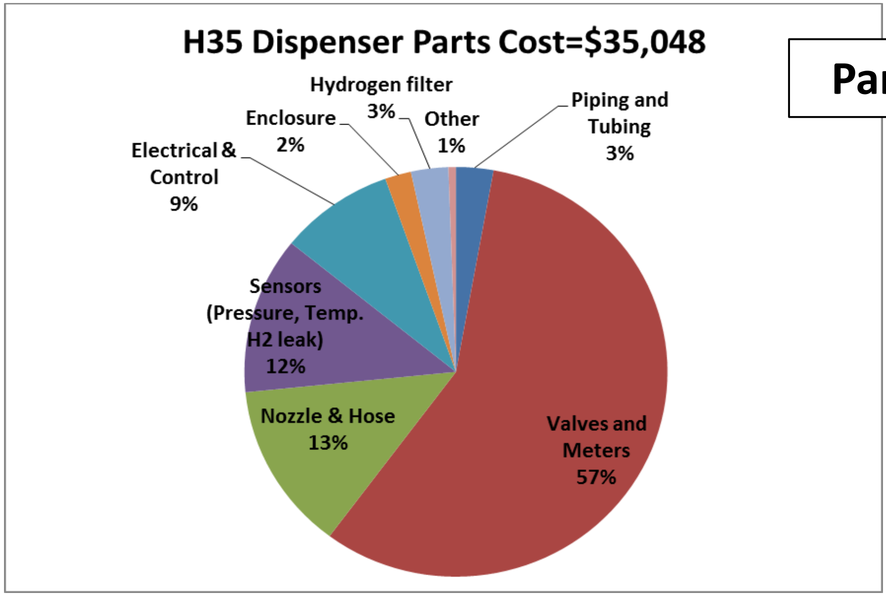
| Single Hose Dispenser H35 | | | | |
|---|---|---|---|---|
| Part No. | Part | Supplier 1 | Required Units | Dispenser ($) |
| 1 | SOLENOID VALVE | Omega | 1 | 715 |
| 2 | Flow Meter | Alicate | 1 | 10000 |
| 3 | Pressure checking/Regulating Valves | Tescom | 1 | 4771 |
| 4 | Pressure Relief Valve | High Pressure Equipment Company | 1 | 658 |
| 5 | Breakaway valve | Oasis | 1 | 3953 |
| 6 | Hydrogen Leak Sensor | SBS | 1 | 695 |
| 7 | IR flame detector | | 2 | 3000 |
| 8 | Pressure sensors | Sensor Solutions | 2 | 600 |
| 9 | Temperature sensors | TempSensing | 1 | 50 |
| 10 | Hydrogen filter | | 1 | 1000 |
| 11 | Piping (10 m required) | Zoro | 10 | 250 |
| 12 | Tubing and Fittings (10 units estimated) | Swagelok | 15 | 750 |
| 13 | Air Actuated valve | Valworx | 1 | 160 |
| 14 | Control Unit | Siemens | 1 | 1000 |
| 15 | Hose (single/double) | NanoSonic | 1 | 100 |
| 16 | Nozzle | OPW | 1 | 4531 |
| 17 | Nozzle Boot | | 1 | 200 |
| 18 | Power Supply | iGem | 1 | 275 |
| 19 | Digital Display | Wayne | 1 | 347 |
| 20 | Card Reader | Ovation | 1 | 149 |
| 21 | Console/keypad | Wayne | 1 | 580 |
| 22 | Console printer | Wayne | 1 | 385 |
| 23 | Fueses (3A; 5A; 10A) | Mersen | 3 | 60 |
| 24 | Relays (3A; 5A; 10A) | Releco | 3 | 75 |
| 25 | k-type thermocouples | Autocalve | 2 | 204 |
| 26 | Enclosure | n/a | 1 | 500 |
| 27 | Shut-down emergency Button | VanTech | 1 | 40 |
| | **Total** | | | **35,048** |

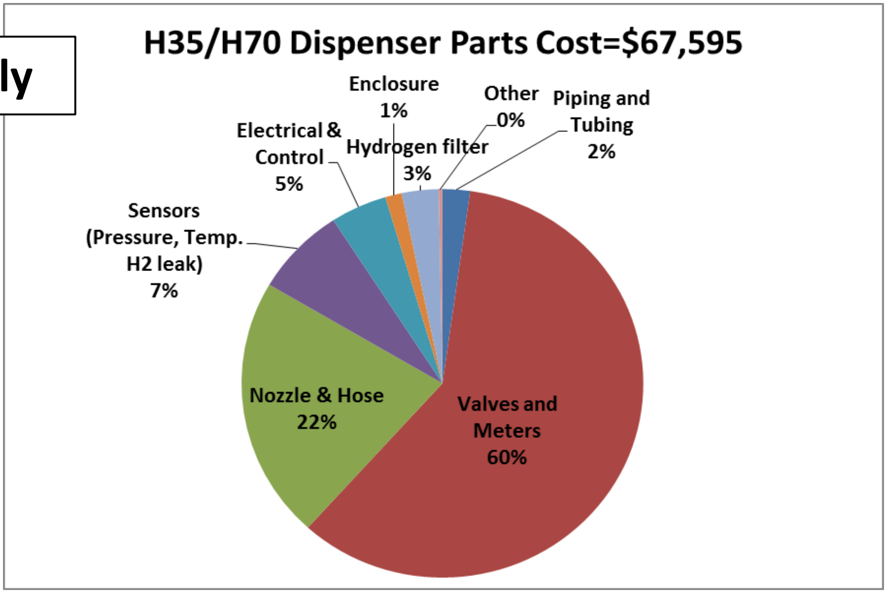
| Dual Hose Dispenser H35/H70 | | | | |
|---|---|---|---|---|
| Part No. | Part | Supplier 1 | Required Units | Cost per Dispenser ($) |
| 1 | SOLENOID VALVE | Omega | 2 | 1430 |
| 2 | Flow Meter | Alicate | 2 | 20000 |
| 3 | Pressure checking/Regulating Valves | Tescom | 2 | 9542 |
| 4 | Pressure Relief Valve | High Pressure Equipment | 2 | 1316 |
| 5 | Breakaway valve | Oasis | 2 | 7906 |
| 6 | Hydrogen Leak Sensor | SBS | 1 | 695 |
| 7 | IR flame detector | | 2 | 3000 |
| 8 | Pressure sensors | Sensor Solutions | 4 | 1200 |
| 9 | Temperature sensors | TempSensing | 2 | 100 |
| 10 | Hydrogen filter | | 2 | 2000 |
| 11 | Piping (20 m required) | Zoro | 20 | 500 |
| 12 | Tubing and Fittings (20 units estimated) | Swagelok | 20 | 1000 |
| 13 | Air Actuated valve | Valworx | 1 | 160 |
| 14 | Control Unit | Siemens | 1 | 1000 |
| 15 | Hose (single/double) | NanoSonic | 2 | 200 |
| 16 | Nozzle | OPW | 2 | 14531 |
| 17 | Nozzle Boot | | 2 | 400 |
| 18 | Power Supply | iGem | 1 | 275 |
| 19 | Digital Display | Wayne | 1 | 347 |
| 20 | Card Reader | Ovation | 1 | 149 |
| 21 | Console/keypad | Wayne | 1 | 580 |
| 22 | Console printer | Wayne | 1 | 385 |
| 23 | Fueses (3A; 5A; 10A) | Mersen | 3 | 60 |
| 24 | Relays (3A; 5A; 10A) | Releco | 3 | 75 |
| 25 | k-type thermocouples | Autocalve | 2 | 204 |
| 26 | Enclosure | n/a | 1 | 500 |
| 27 | Shut-down emergency Button | VanTech | 1 | 40 |
| | **Total** | | | **67,595** |

Accomplishment and Progress

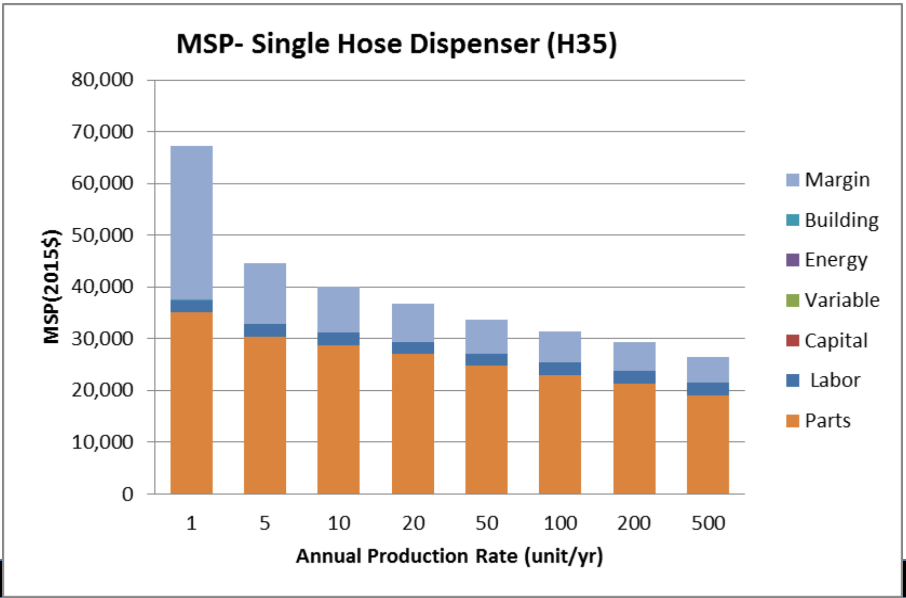
# Dispenser Cost Analysis

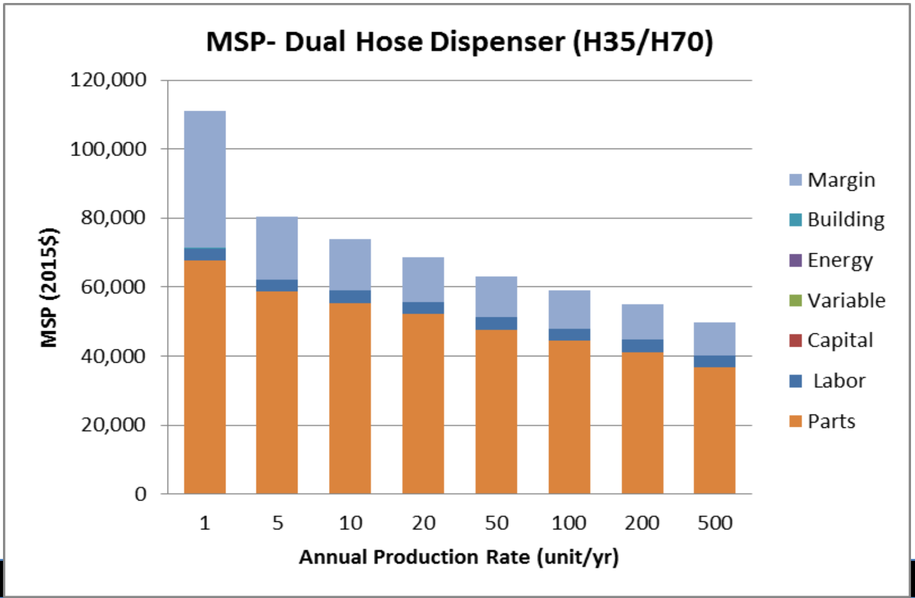
**Parts Only**



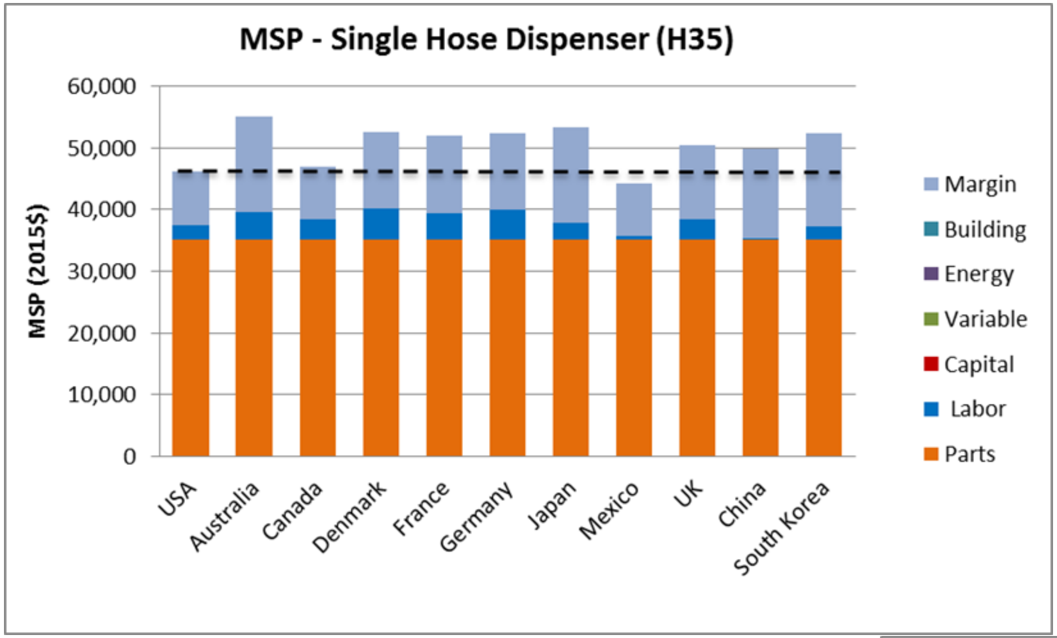




Parts & Assembly Cost (assuming 20% discount per 10x increase in purchased quantity)

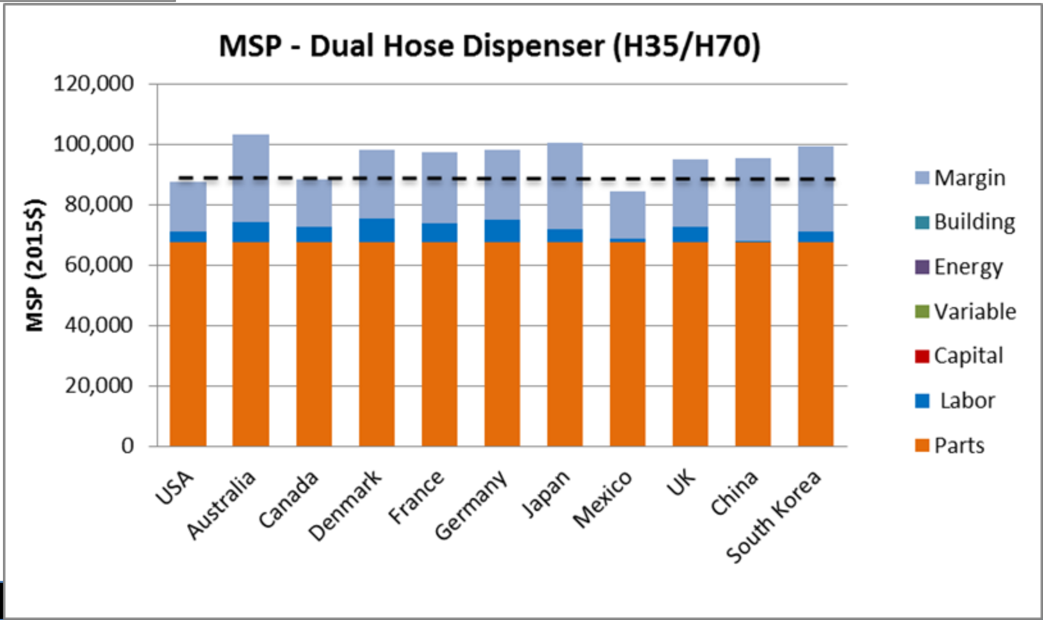


# Minimum Sustainable Price - Dispenser

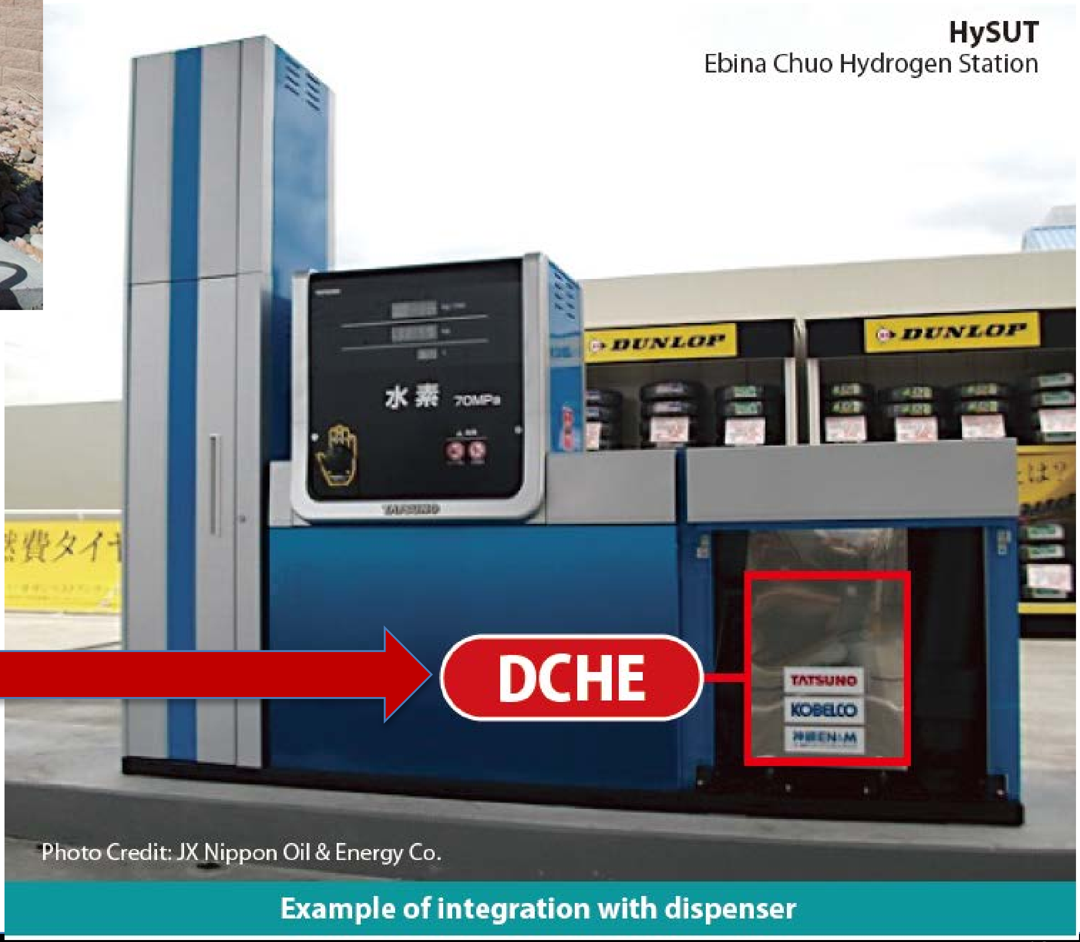



- United States advantages are: lower shipping and interest rates and longer experience in this field
- Mexico's advantage relative to the U.S. is driven by lower labor and building costs



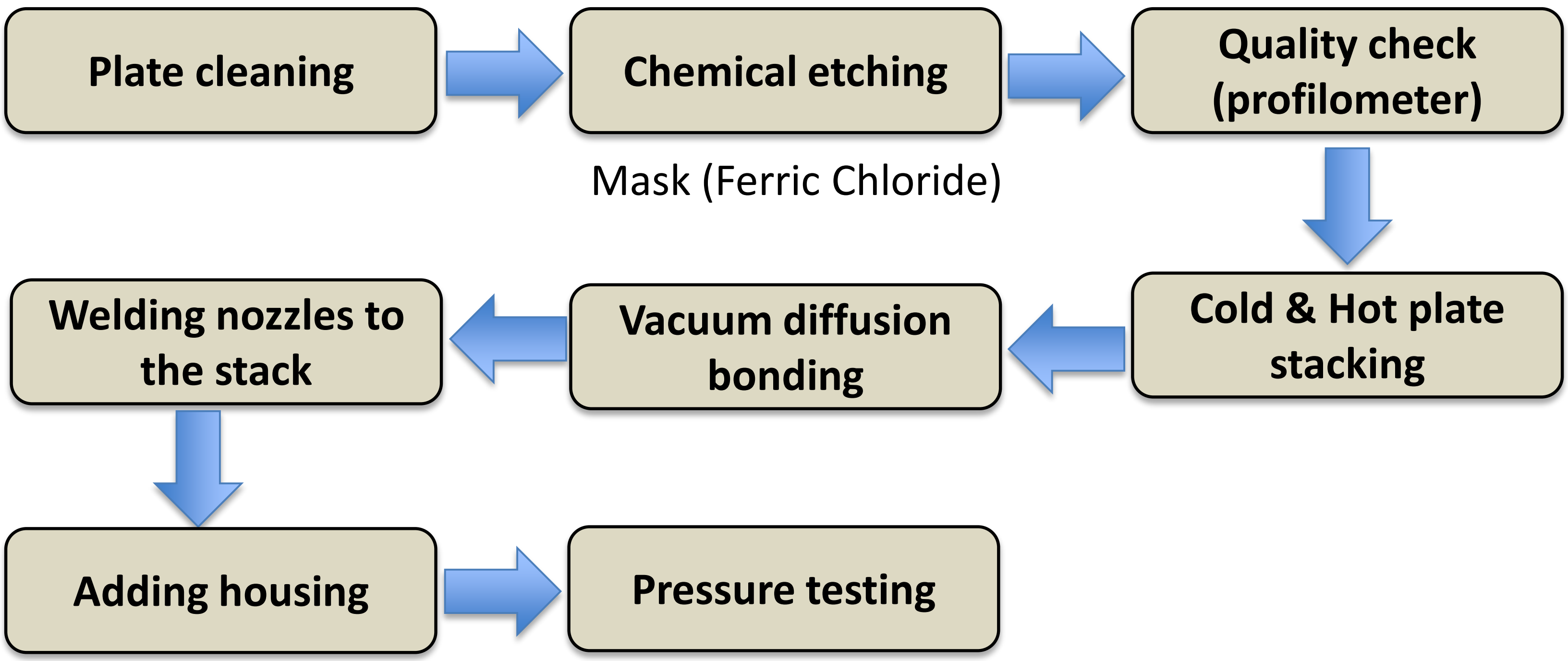
# Advance Heat Exchanging Technology


**DCHE**: **D**iffusion Bonded
**C**ompact **H**eat **E**xchanger



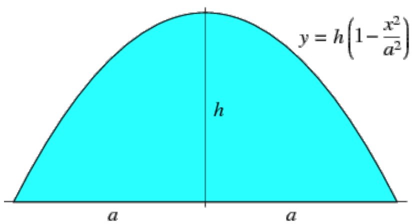

Images for: NREL HRS and Kobelco DCHE

# Microchannel Heat Exchanger - Process Flow

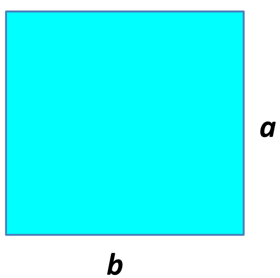



- Chemical etching can be replaced by laser grooving.
- Laser grooving speed= 300 mm/min

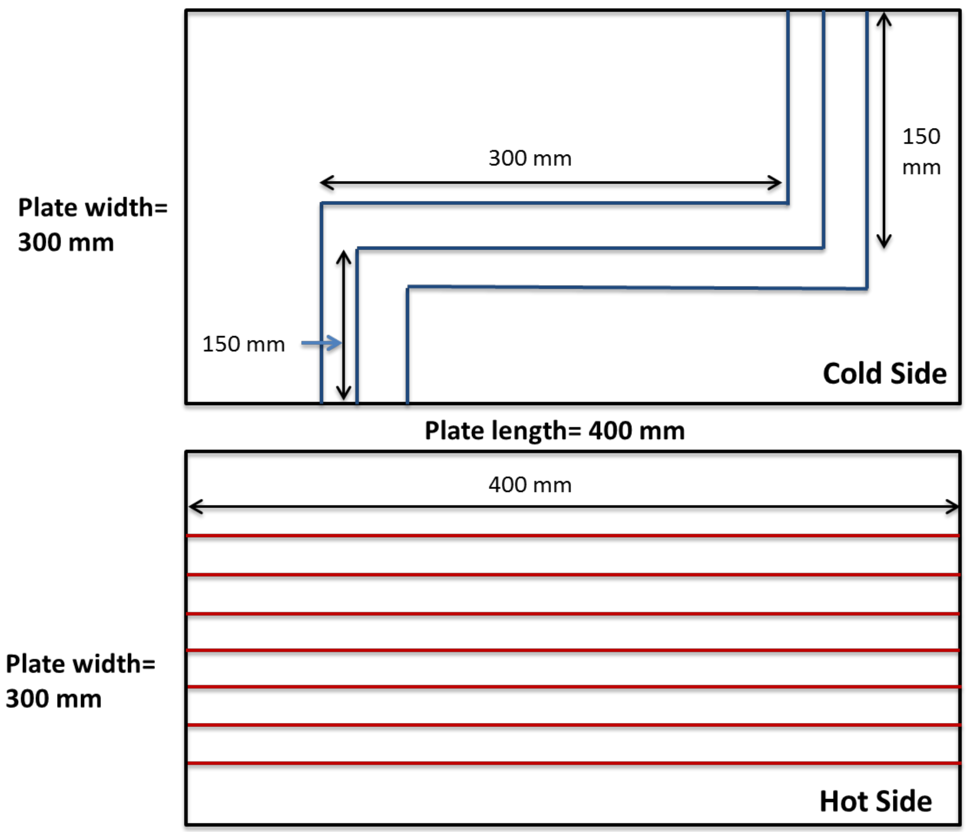
# Plate Design Parameters




**Parabolic Channels**




**Square Channels**

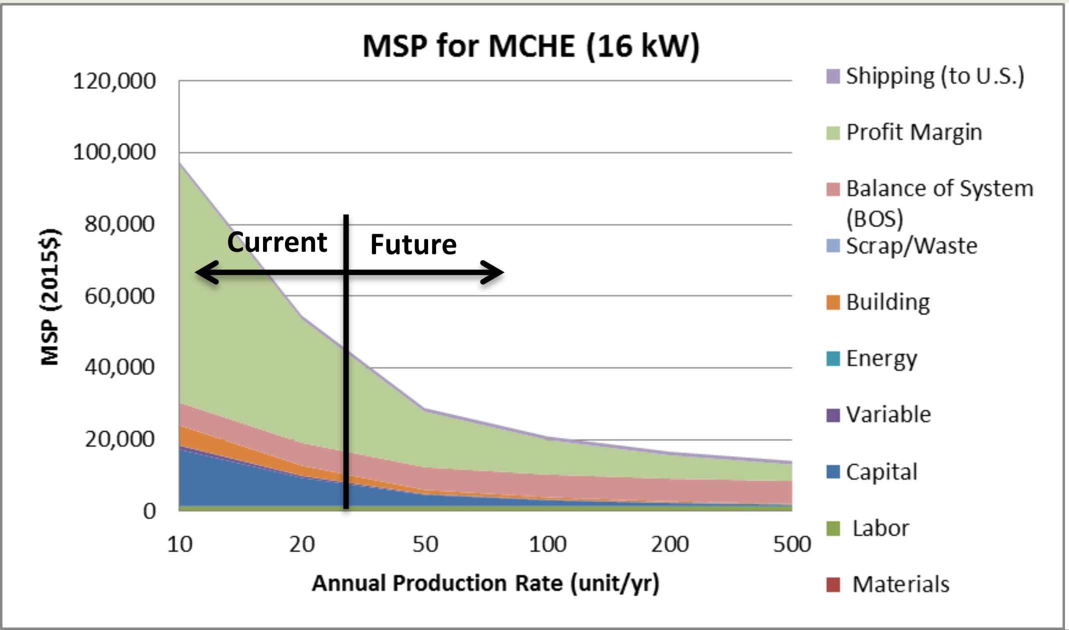



**Chosen Design**

| Individual Plate Size= 400*300 mm$^2$=375,000 mm$^2$<br>Distance between Individual Channels= 750 µm | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Parabolic Channel Design Channel Parameters | | | | | Square Channel Design Channel Parameters | | | |
| a (mm) | h (mm) | Arc Length (mm) | Plate Thickness (mm) | Transfer Area of Individual Channel (mm2) | a (mm) | b (mm) | Plate Thickness (mm) | Square Channel-Transfer Area of Individual Channel (mm2) |
| 0.125 | 0.20 | 0.897 | 0.500 | 458.97 | 0.25 | 0.25 | 0.500 | 400.00 |

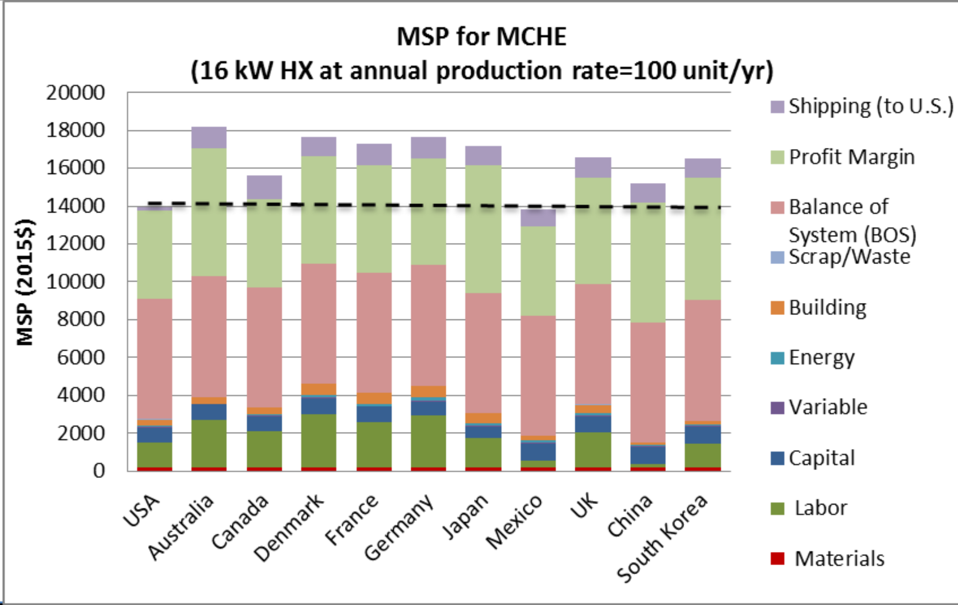
# Accomplishment and Progress

# Minimum Sustainable Price - MCHE




## MCHE: Microchannel Heat Exchanger

- 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



# Accomplishment and Progress

# HRS Capital Cost and $H_2$ Price

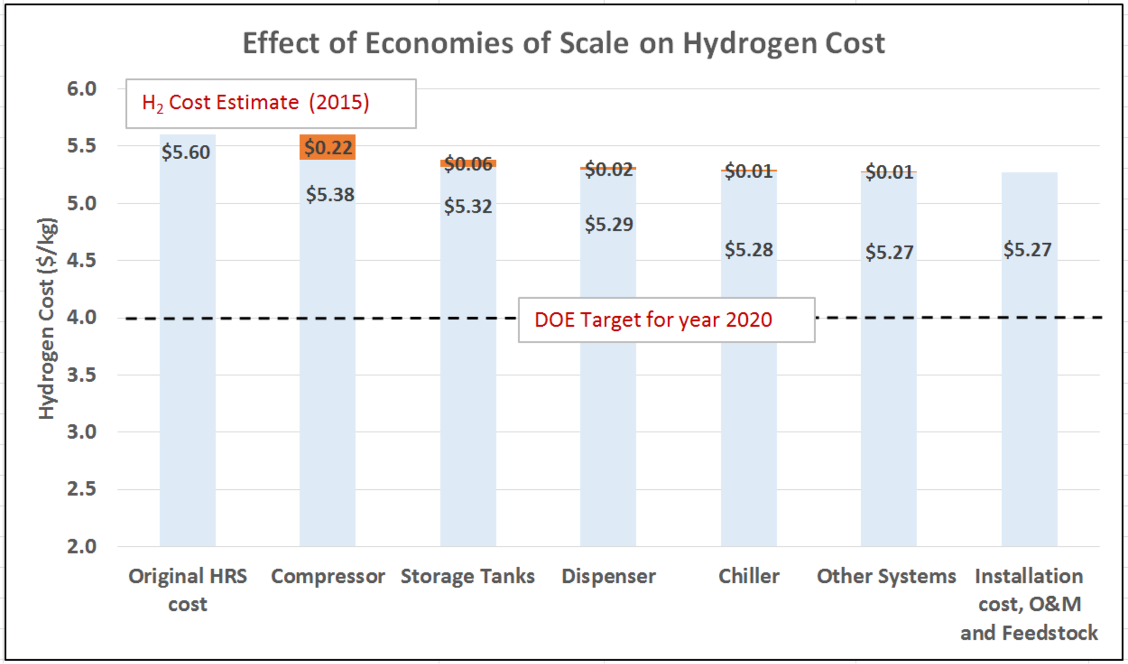
| | Actual Cost (X$1,000) | Future Cost (X$1,000) @ 10 units/yr | Future Cost (X$1,000) @ 100 units/yr |
|---|---|---|---|
| Capital Cost FirstElement HRS in California | 2,050 | | |
| Installation cost, O&M and Feedstock | n/a | n/a | n/a |
| Compressor | 121 | 55 | 45 |
| Storage Tanks | 166 | 117 | 56 |
| Dispenser | 270 | 75 | 55 |
| Chiller | 150 | 100 | 80 |
| Other Systems | 900 | 450 | 400 |
| Installation cost | 408 | 408 | 408 |
| **Future HRS Installed Cost** | **2,015** | **1,205** | **1,044** |

1 kg $H_2$ ≈ 1 gallon of gasoline equivalent (gge)

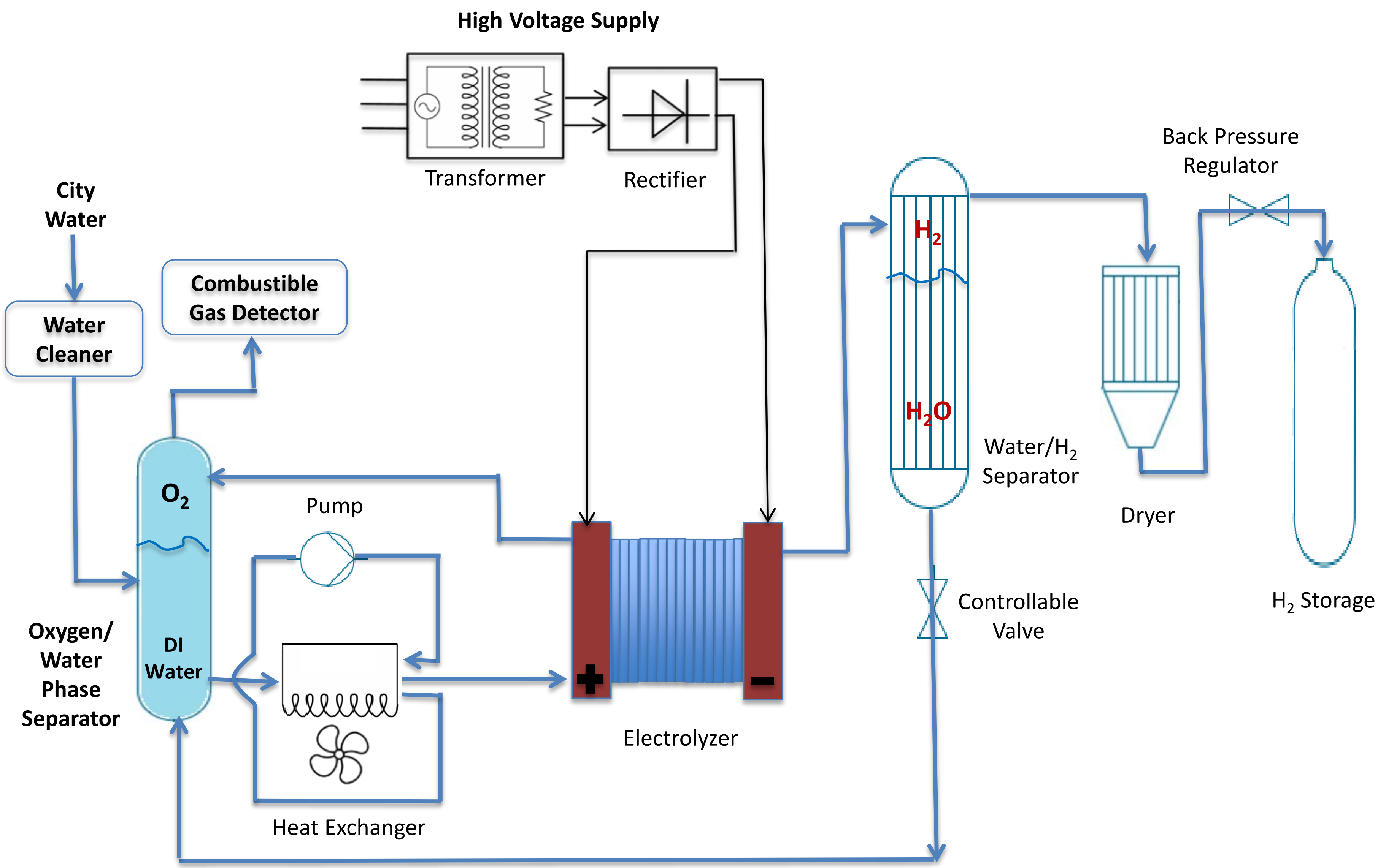
| | 2016 Hyundai Tucson Fuel Cell | 2016 Toyota Mirai |
|---|---|---|
| |  |  |
| | **Fuel Economy and Related Estimates** | |
| Fuel Economy (mi/kg) | **50** comb, 49 city, 51 hwy | **66** comb, 66 city, 66 hwy |
| Range (miles) | 265 | 312 |
| Annual Fuel Cost * | $1,700 | $1,250 |

## 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

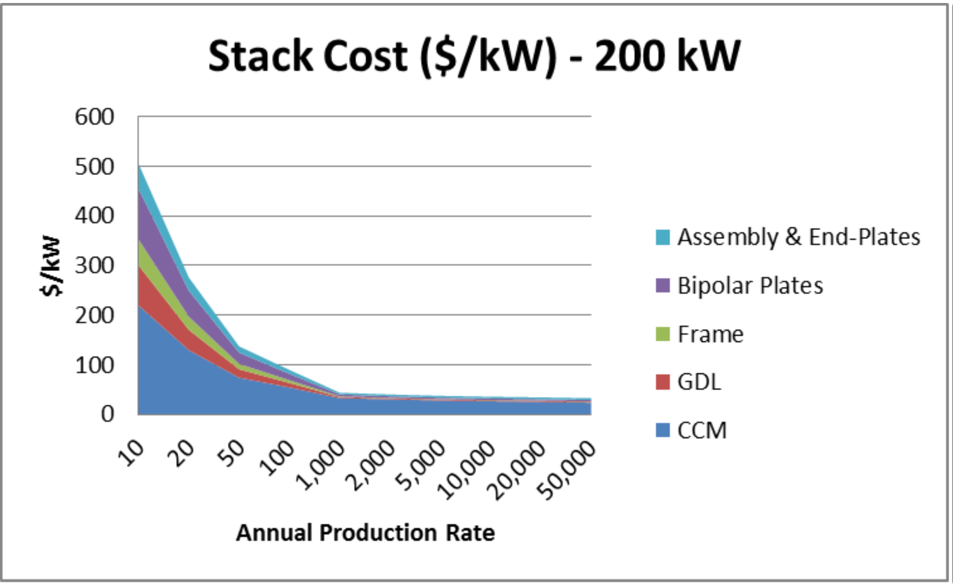


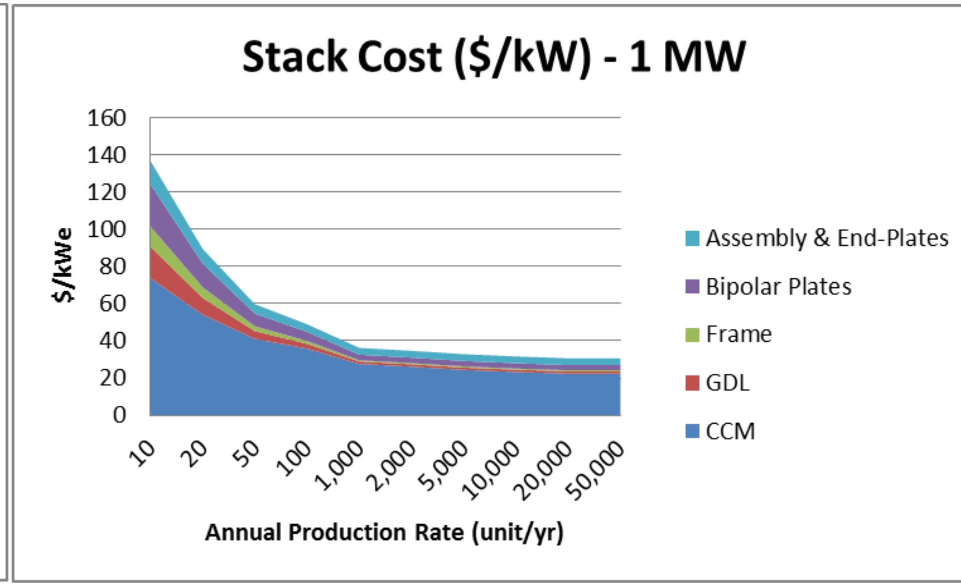
# Schematic of PEM Electrolysis System

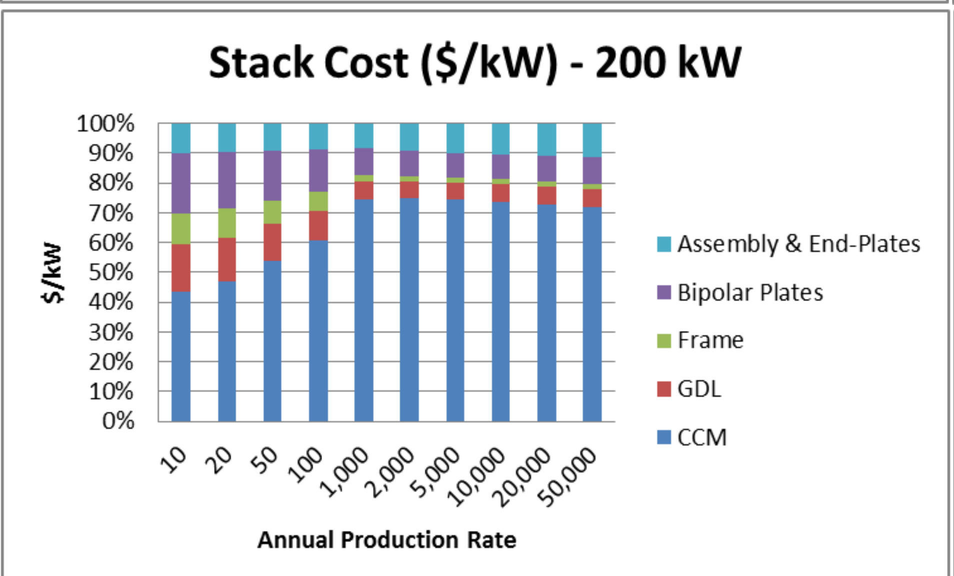


Accomplishment and Progress

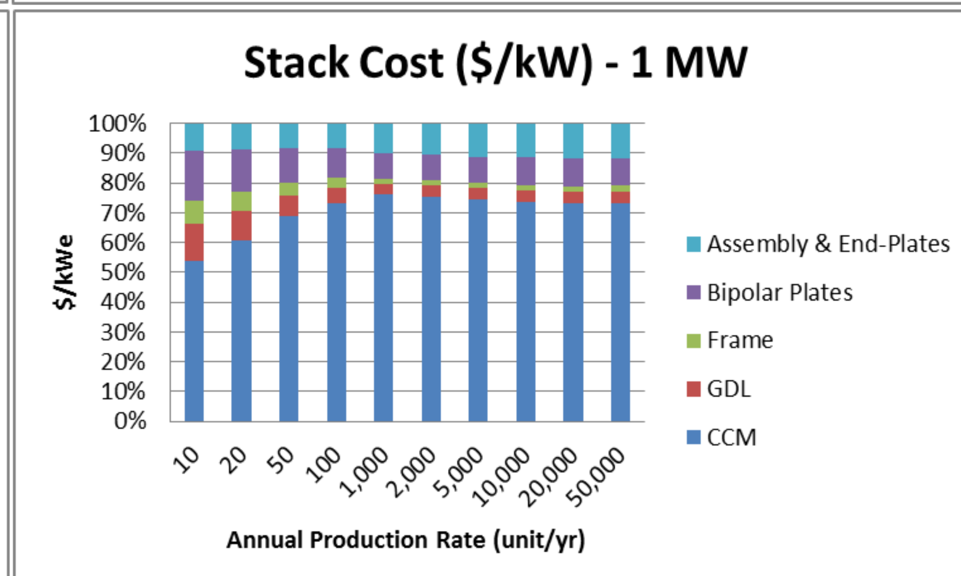
# PEM Electrolyzer Stack Cost – Preliminary




65 kg $H_2$/day




325 kg $H_2$/day

# Remaining Challenges and Barriers

Challenges we face in this study:

- Involve more organizations (industry, part suppliers, regulation agencies, etc.) in the hydrogen refueling station study
- Establish new collaboration with industry for the ongoing project (manufacturing competiveness of the onsite hydrogen production equipment)
- Lack of competition between part suppliers (e.g. nozzles and hoses) make it hard to study potential cost reductions

# Proposed Future Work

- Complete manufacturing cost analysis for other HRS's systems (e.g., onsite hydrogen production systems)
  - PEM electrolyzers
  - Alkaline electrolyzers
  - Small size steam methane reformers

- Study effect of future technologies and economies of scale on the HRS capital cost and hydrogen prices

# Responses to 2016 AMR Reviewer Comments

- NREL should discuss how the researchers will transfer this information to industry.
- The project should reach out to existing manufacturers and developers to review the results and the assumptions that drive the models.

**In addition to the continuous work we do with industry, we got the chance to work with California Energy Commission (CEC) and ZEV office at the California Governor's office.**

- The project should bring in companies that are innovating away from the traditional and mature systems and components—technology readiness levels 6 and 7.

**Our team is trying hard to collaborate with researchers and manufacturers in such area, for example we recently started to work with some manufacturers of new microchannel heat exchanger technology that has been proven to reduce the cost at the long run and have better heat exchanging capabilities than classical double tube heat exchangers**

- It would have been interesting if some effort was spent on durability and operating expenditures (OPEX).

**While this project focuses on manufacturing cost and supply chain analyses, we agree that OPEX is important area that needs further investigation. We will work with FCTO to propose some ideas of optimizing manufacturing and operation cost of some technologies used in the hydrogen stations.**

- It is not clear whether the models are used only for helping DOE assess status. Impact could be larger if these models are shared and used by the developers.

**We already established sort of collaboration with industry and hope to expand this network. We will also work with FCTO and CEC to publicize our findings and insights. We are also planning to attend some conferences in Europe and Asia to publicize and promote the importance of this work.**

# Collaborations

- Kriston Brooks, Pacific Northwest National Lab (PNNL)
  - Provided critical inputs for manufacturing cost analysis for heat exchangers
- Amgad Elgowainy, 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 $H_2$ compressors for Japanese market
- Sean Shunsuke Chigusa, Kobelco Compressors, Japan/USA
  - Provided some inputs for hydrogen compressor
- 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**: to provide a framework for technoeconomic 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, dispensers, chillers and heat exchangers, and onsite hydrogen production equipment
  - Trade flow maps for global HRSs
- **Collaboration**: Sandia, ANL and PNNL
- **Proposed Next-Year Research**:
  - Complete manufacturing cost models for onsite hydrogen production equipment
  - Complete supply chain analysis and trade flow mapping for onsite hydrogen production equipment
  - Investigate effect of qualitative factors in the manufacturing competitiveness

# Technology Transfer Activities

- Not applicable for this cost analysis

# Thank you

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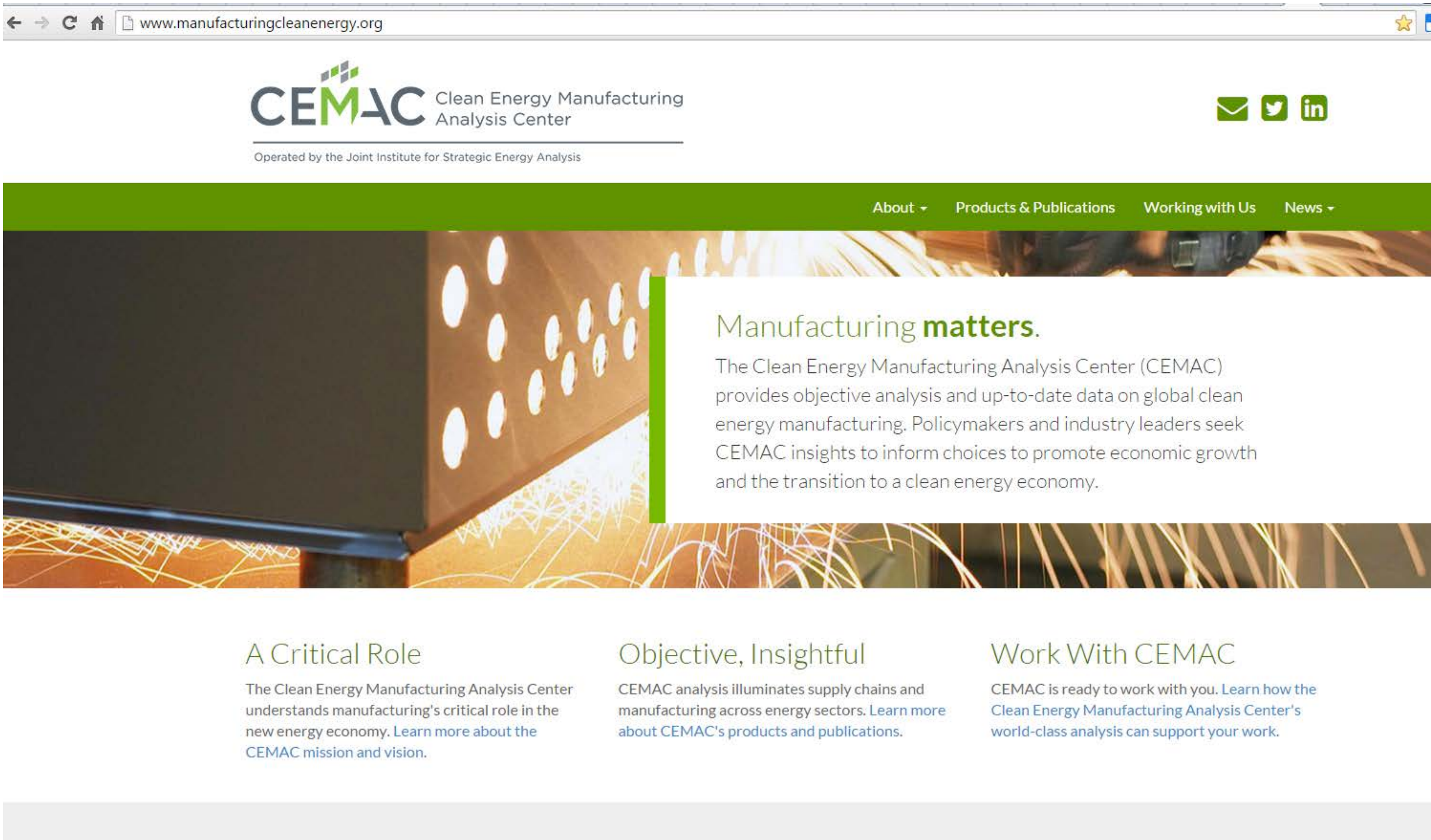
www.manufacturingcleanenergy.org

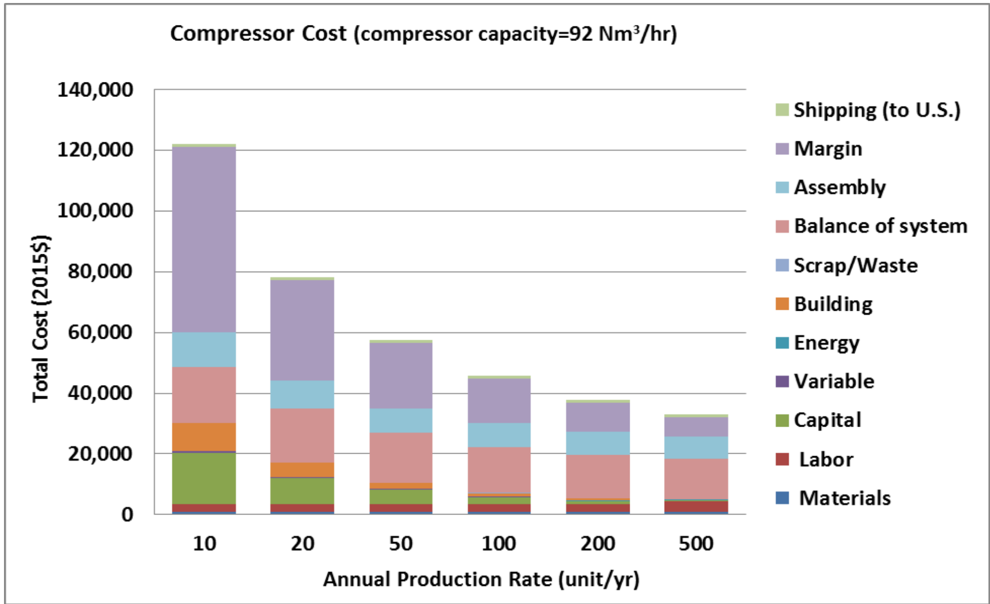


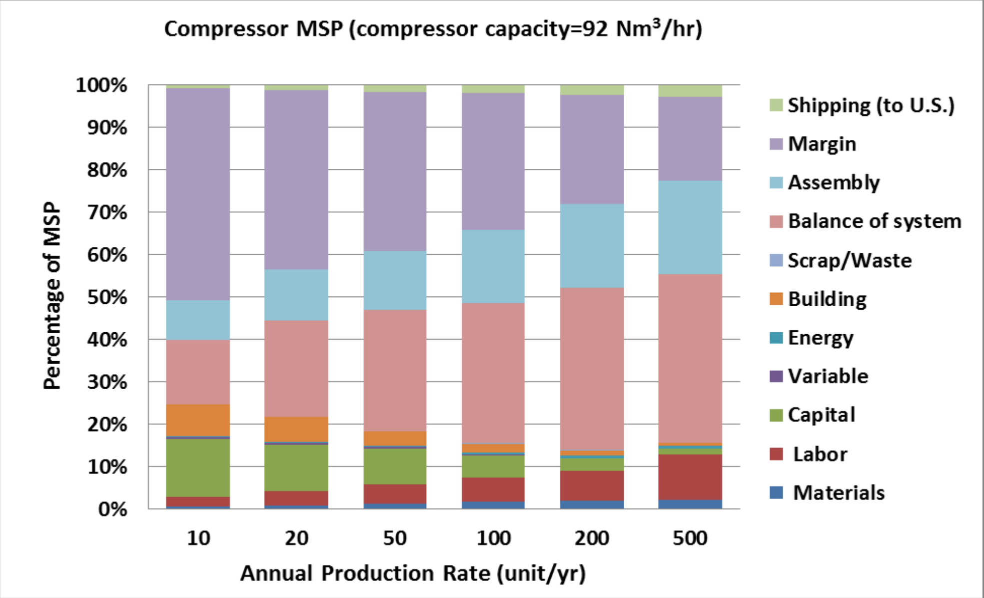
# Backup Slides

# Minimum Sustainable Price - Compressor

**Assumptions**

- 1 stage compressor
- Compression ratio < 7
- $P_{in}$= 150-200 bar, $P_{out}$= 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
- Shipping cost is assumed for shipping compressors from East Coast to West Coast in this example

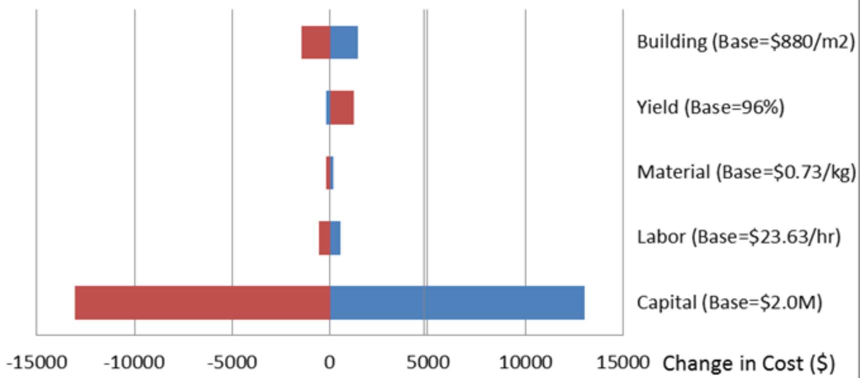


# Sensitivity Analysis

**U.S. Plant**

**Compressor Manufacturing Cost=$121,080**
**92 Nm3/hr @ 10 compressors/yr**

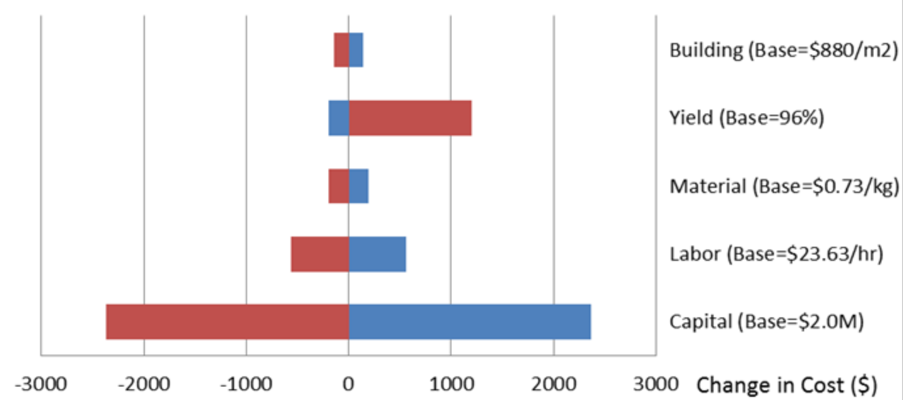



| | Capital (Base=$2.0M) | Labor (Base=$23.63/hr) | Material (Base=$0.73/kg) | Yield (Base=96%) | Building (Base=$880/m2) |
|---|---|---|---|---|---|
| +20% | $13,047 | $567 | $196 | -$180 | $1,438 |
| -20% | -$13,047 | -$567 | -$196 | $1,205 | -$1,438 |

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

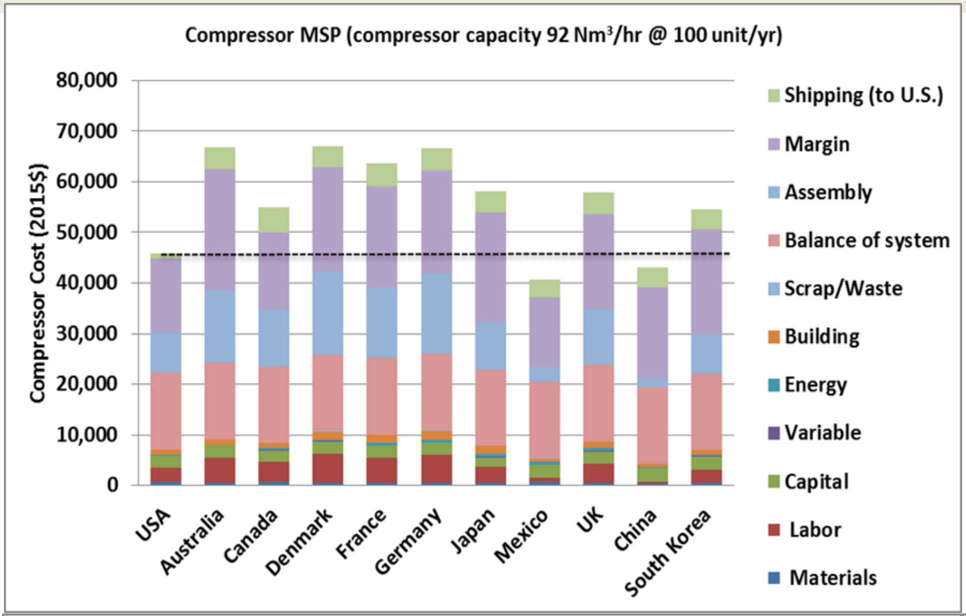
**U.S. Plant**

**Compressor Manufacturing Cost=$44,833**
**92 Nm3/hr @ 100 compressors/yr**

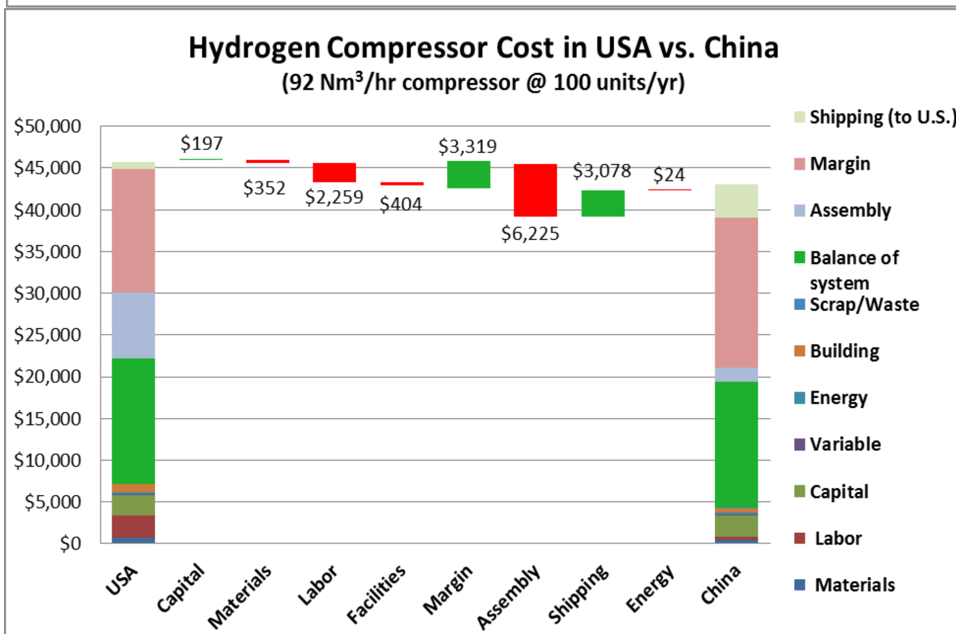


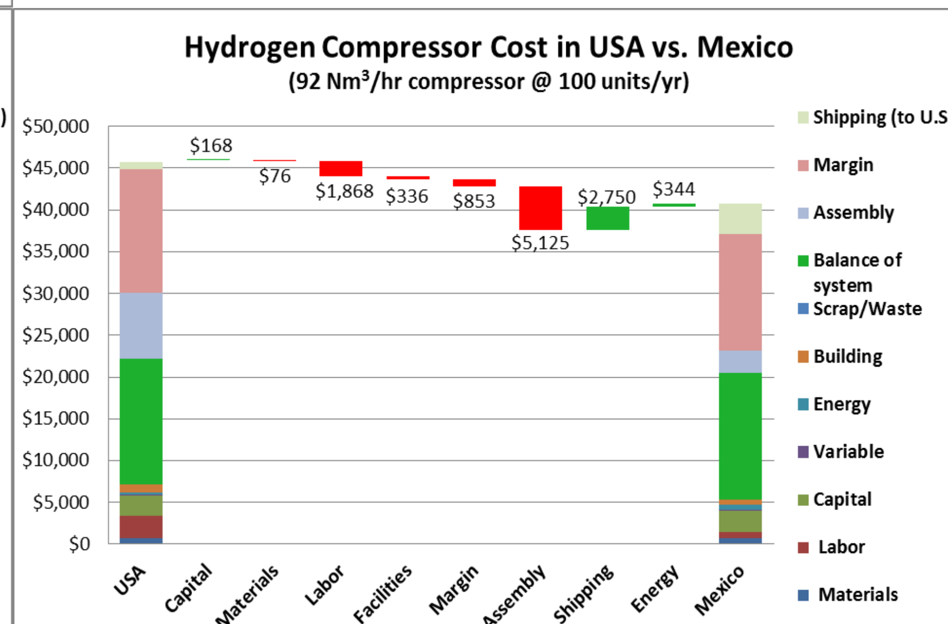

| | Capital (Base=$2.0M) | Labor (Base=$23.63/hr) | Material (Base=$0.73/kg) | Yield (Base=96%) | Building (Base=$880/m2) |
|---|---|---|---|---|---|
| +20% | $2,368 | $559 | $196 | -$193 | $144 |
| -20% | -$2,368 | -$559 | -$196 | $1,201 | -$144 |

# Minimum Sustainable Price - Compressor

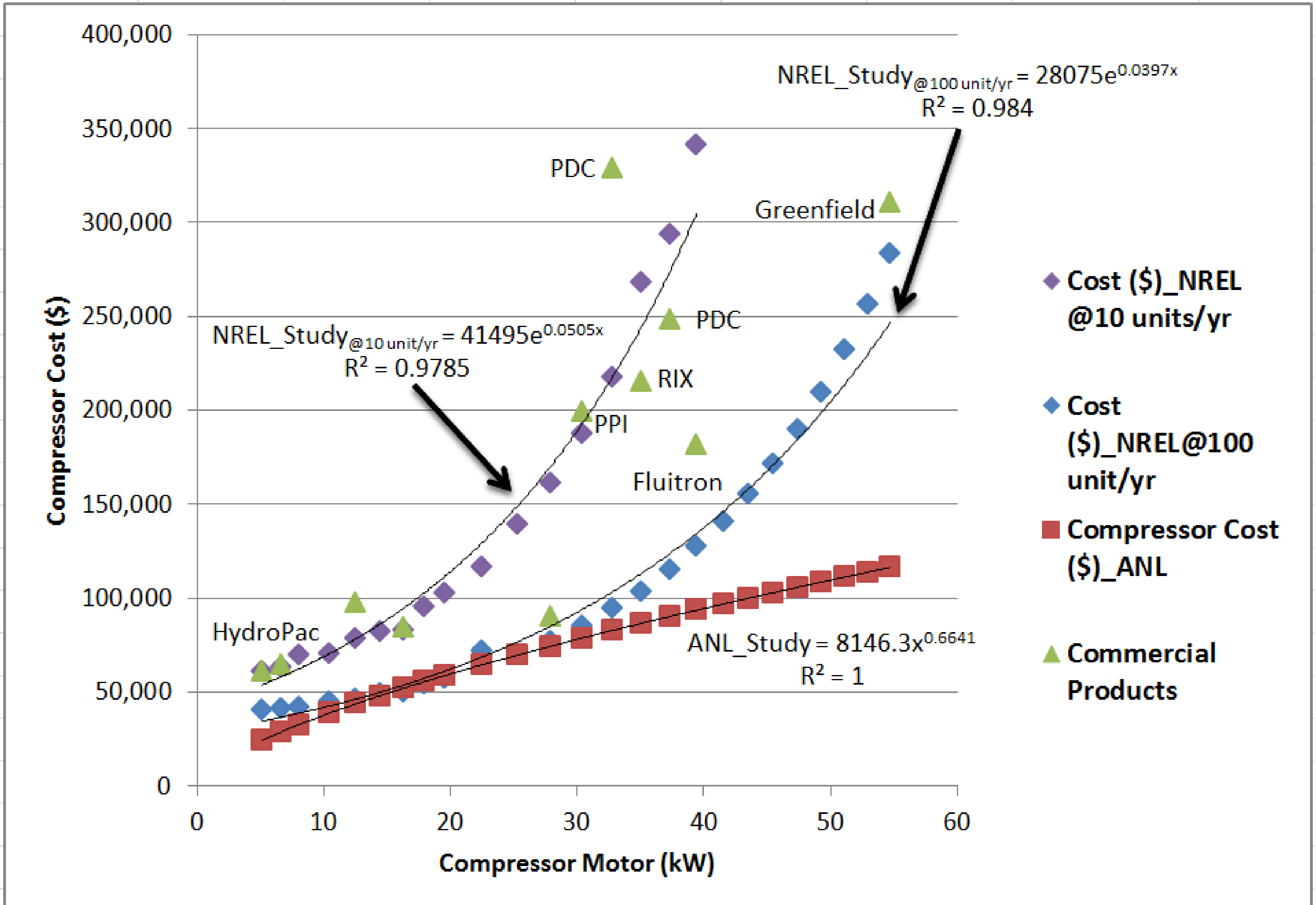



- United States advantages are lower shipping and interest rates and longer experience in this field
- China's advantage relative to the U.S. is driven by lower labor, low material cost, building and energy costs
- Mexico's advantage relative to the U.S. is driven by lower labor and building costs



# Estimation of Compressor Cost




**Annual inflation rate= 2%**

# 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