Manufacturing Competitiveness Analysis for Hydrogen Refueling Stations

Department of Energy Annual Merit Review for Fuel Cell Research

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National Renewable Energy Laboratory

Project ID #
MN017

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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

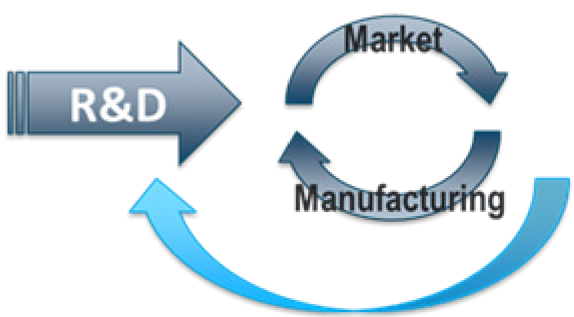
- Sandia National Labs
- Argonne National lab
- Pacific Northwest National Lab
- Other Industry Advisors and Experts

CEMAC Clean Energy Manufacturing Analysis Center

Operated by the Joint Institute for Strategic Energy Analysis

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.

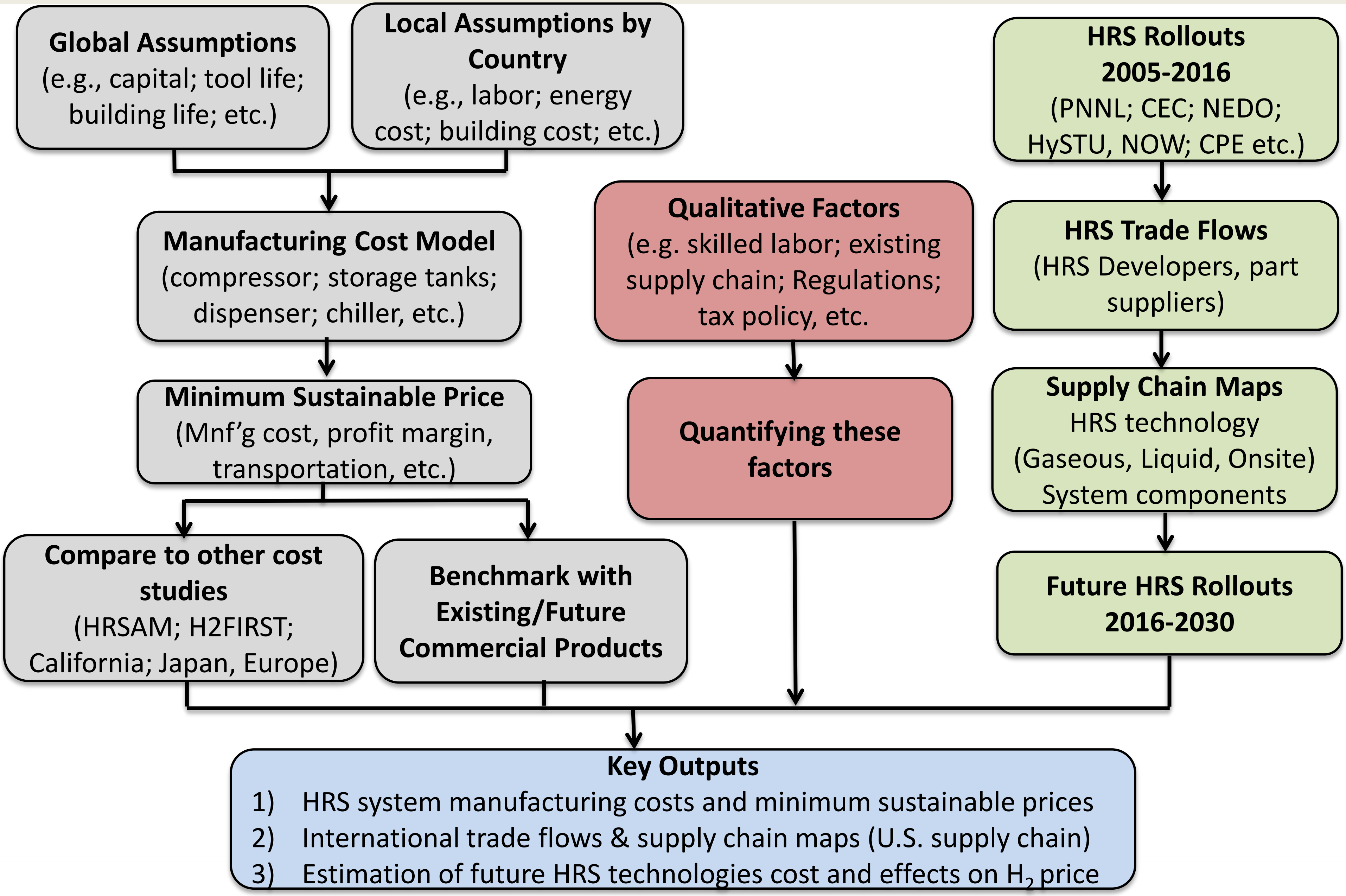
CEMAC was established in 2015 by the U.S. DOE's Clean Energy Manufacturing Initiative.



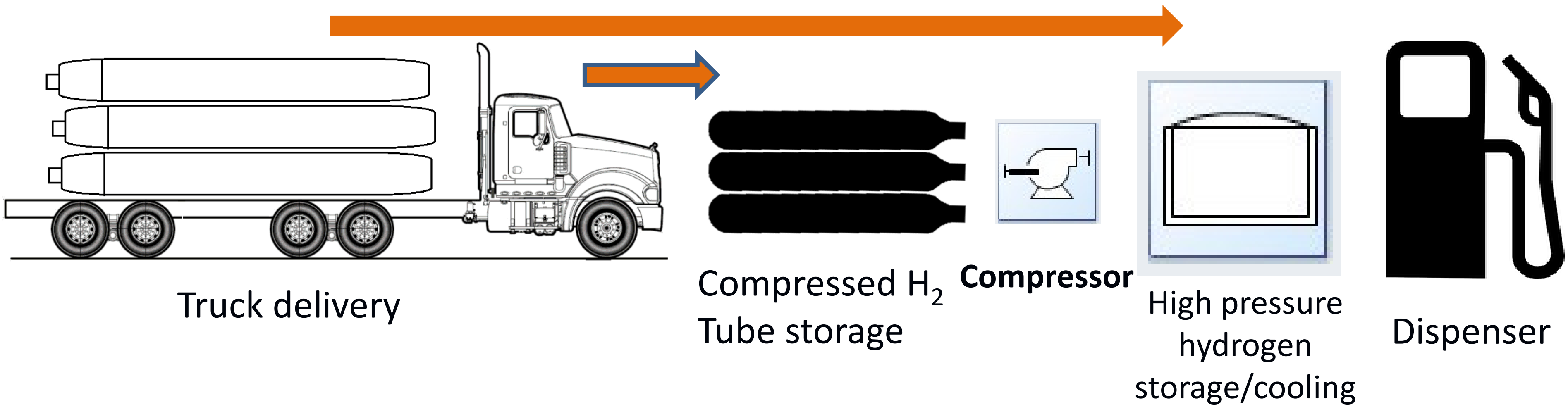
Relevance & Goals

- 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

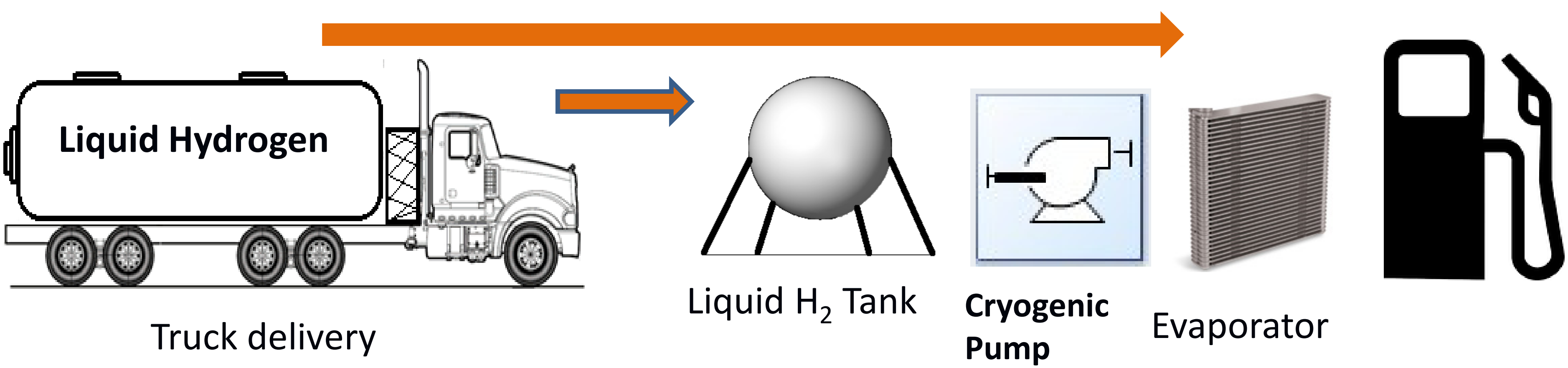
Approach


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
(Mnf'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; HySTU, NOW; CPE 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

Approach: Hydrogen Delivery to the HRS



A configuration of a hydrogen station with gaseous hydrogen delivery



A configuration of a hydrogen station with liquid hydrogen delivery

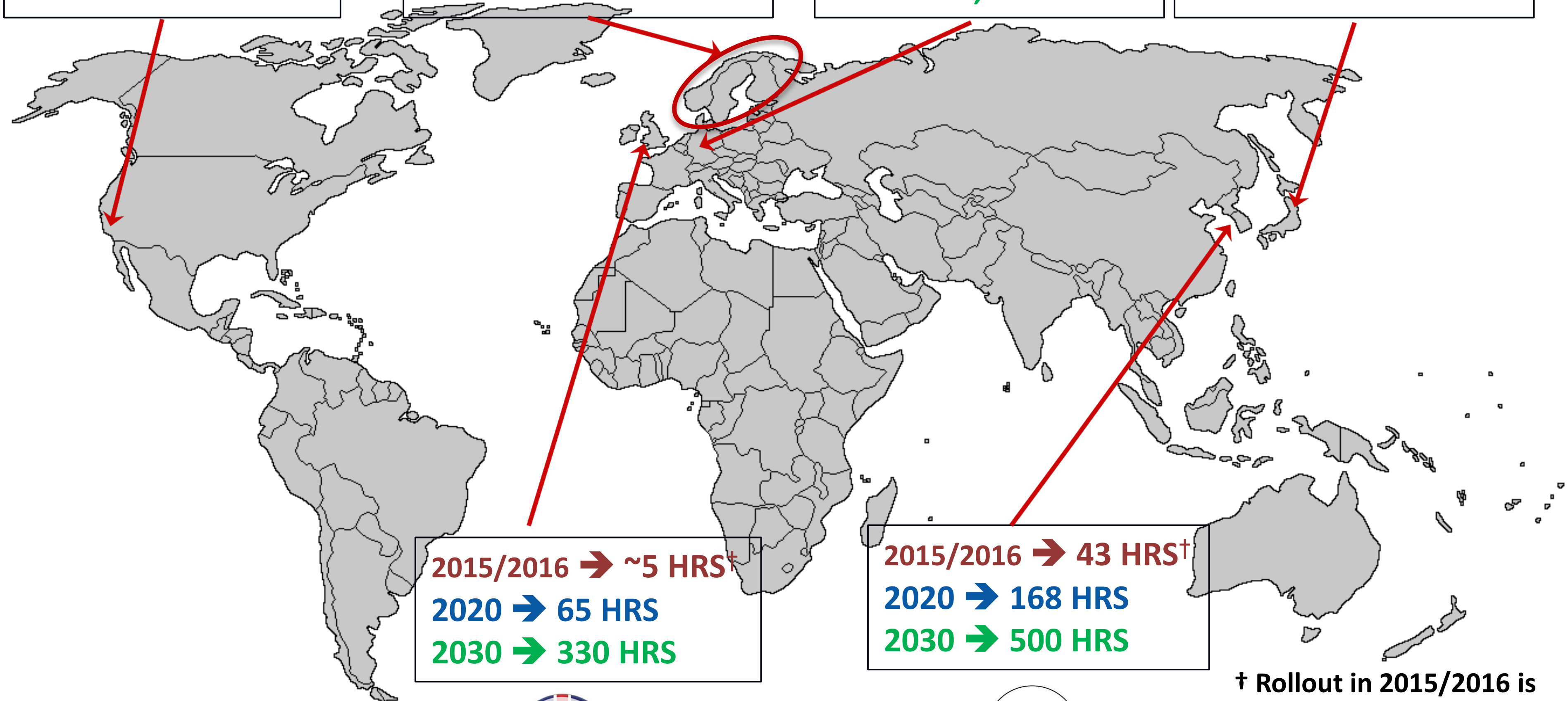
Accomplishments: International HRS Rollouts

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

2015/2016 → ~15 HRS†
2020 → 185 HRS
2030 → 500 HRS

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

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



2015/2016 → ~5 HRS†
2020 → 65 HRS
2030 → 330 HRS

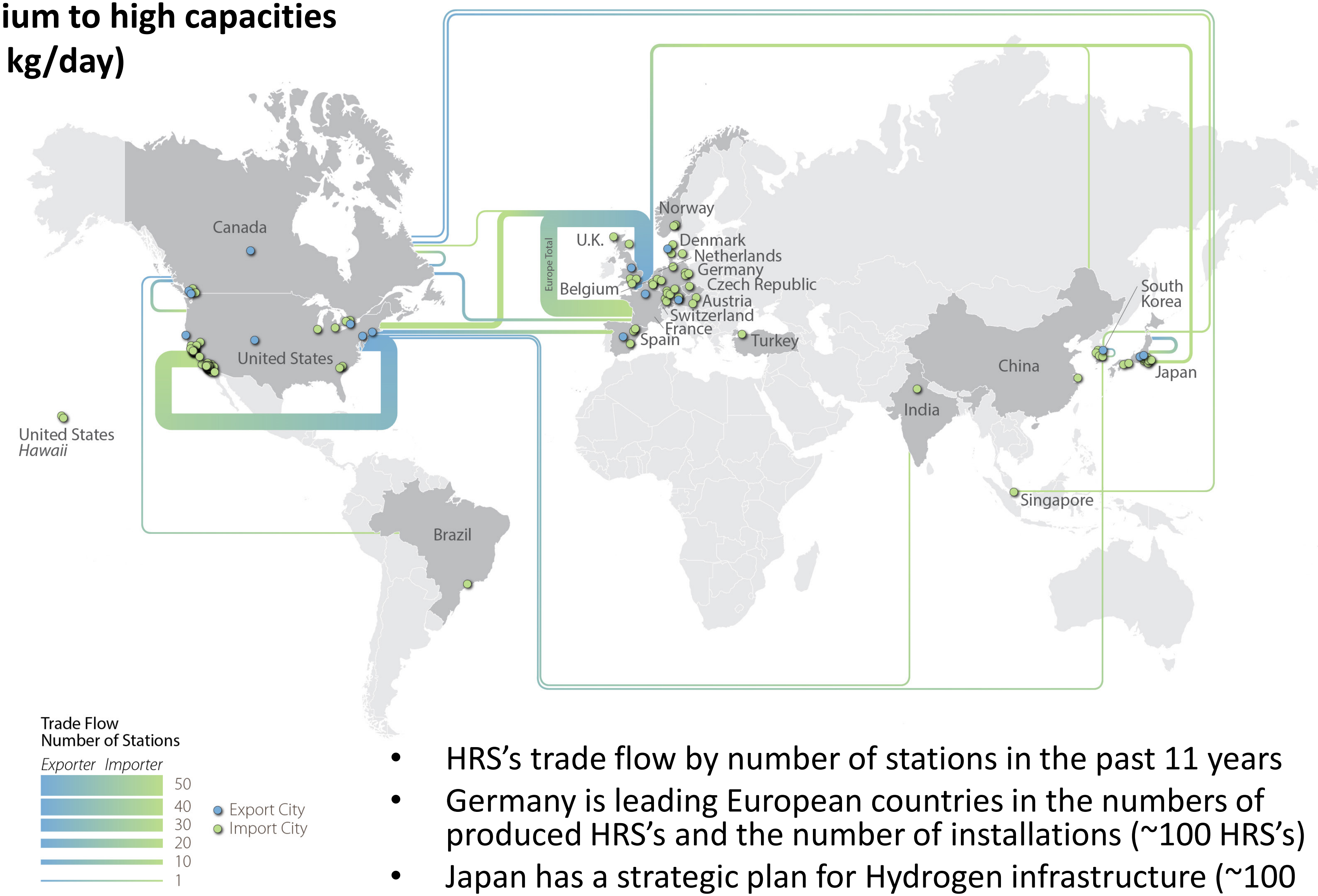
2015/2016 → 43 HRS†
2020 → 168 HRS
2030 → 500 HRS

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

HRS: Hydrogen Refueling Station

Accomplishments: HRS Trade Flows Map

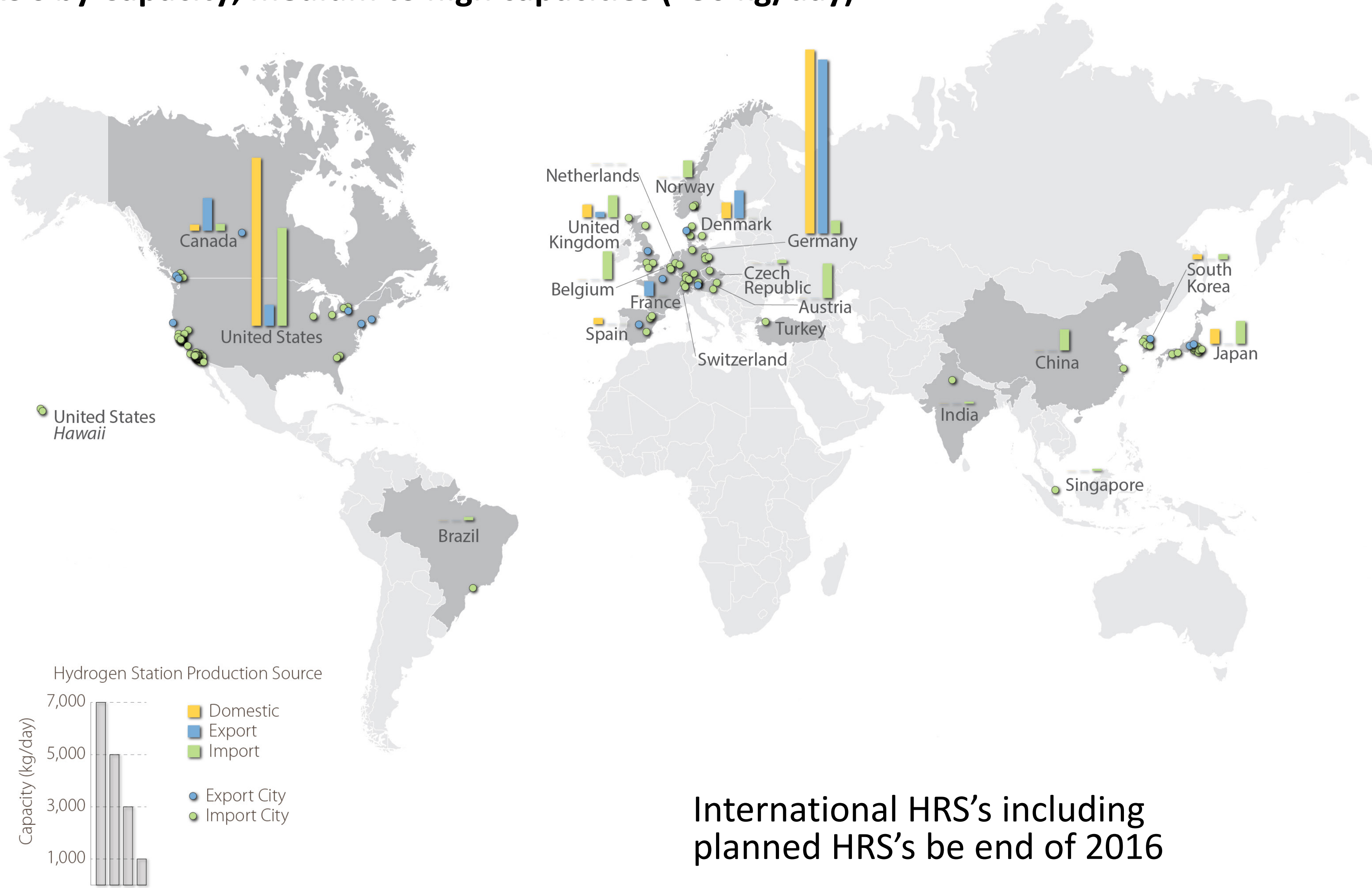
Medium to high capacities (>50 kg/day)



- 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)

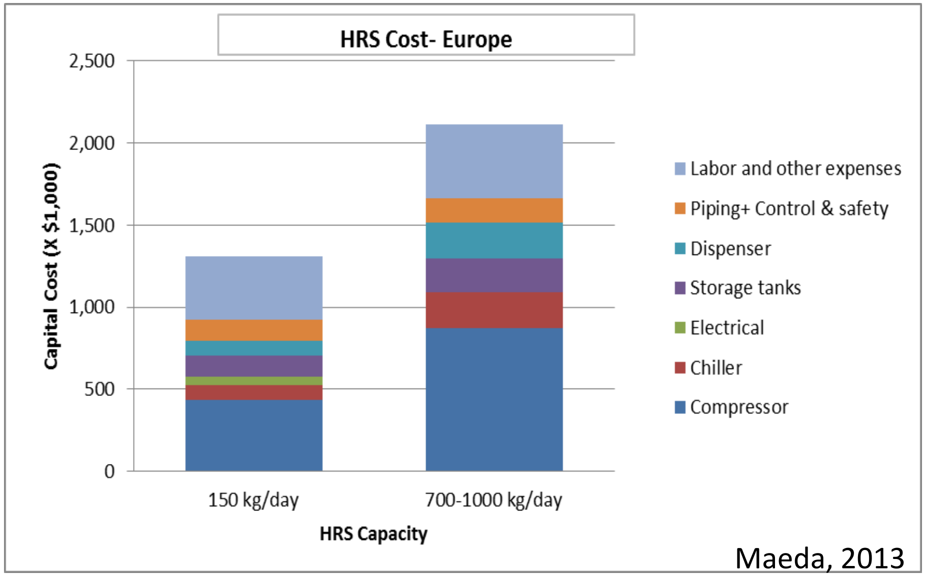
Accomplishments: HRS Flow Map

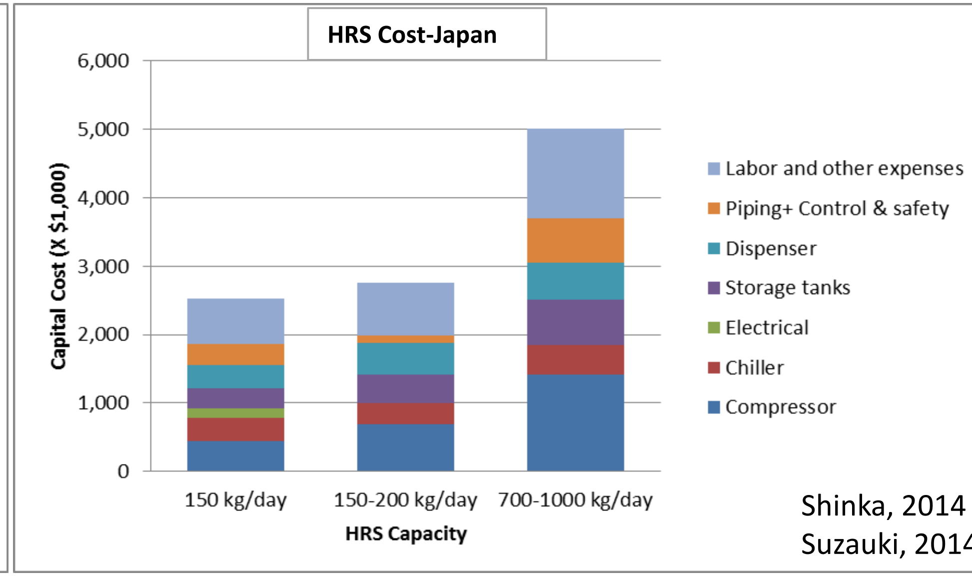
HRS's by Capacity; medium to high capacities (>50 kg/day)

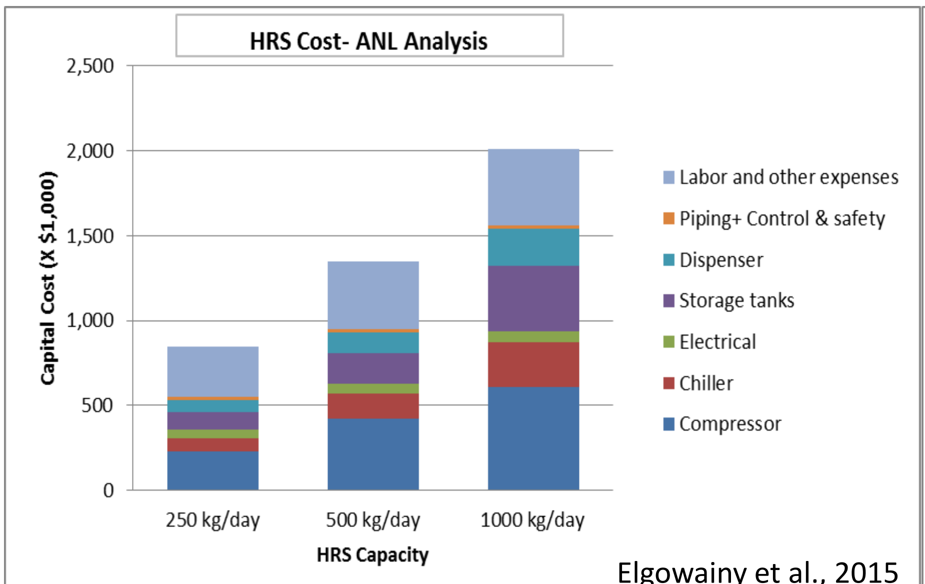


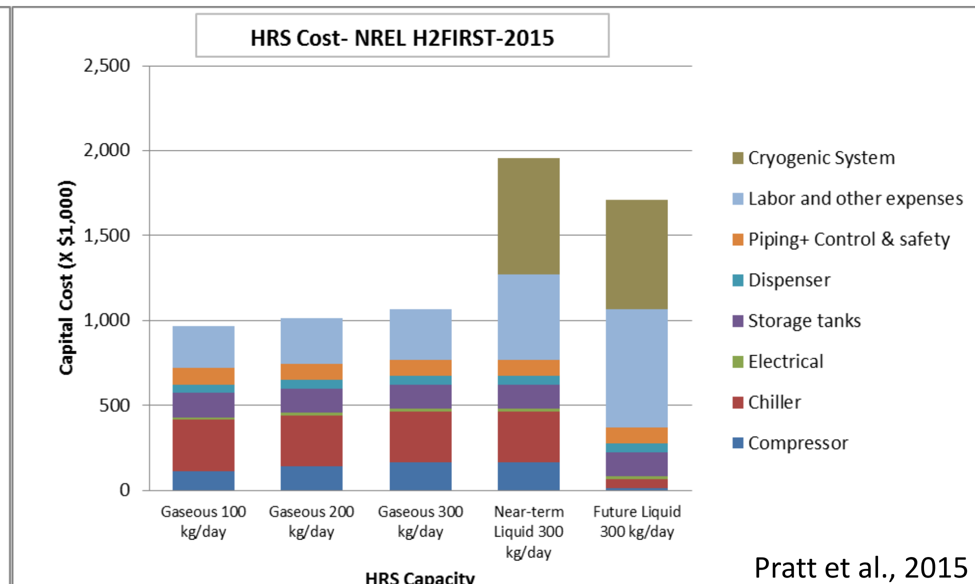
International HRS's including planned HRS's be end of 2016

Accomplishments: HRS Capital Cost



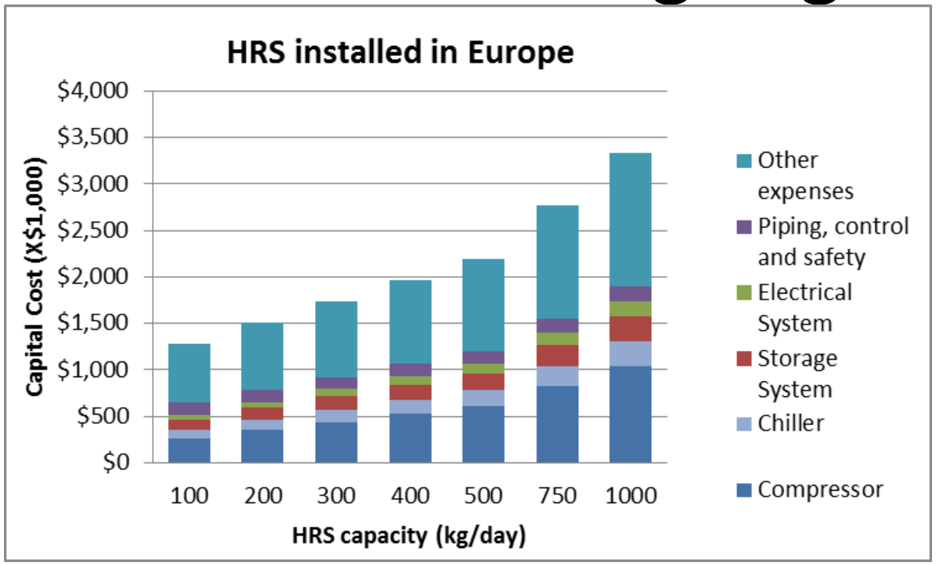


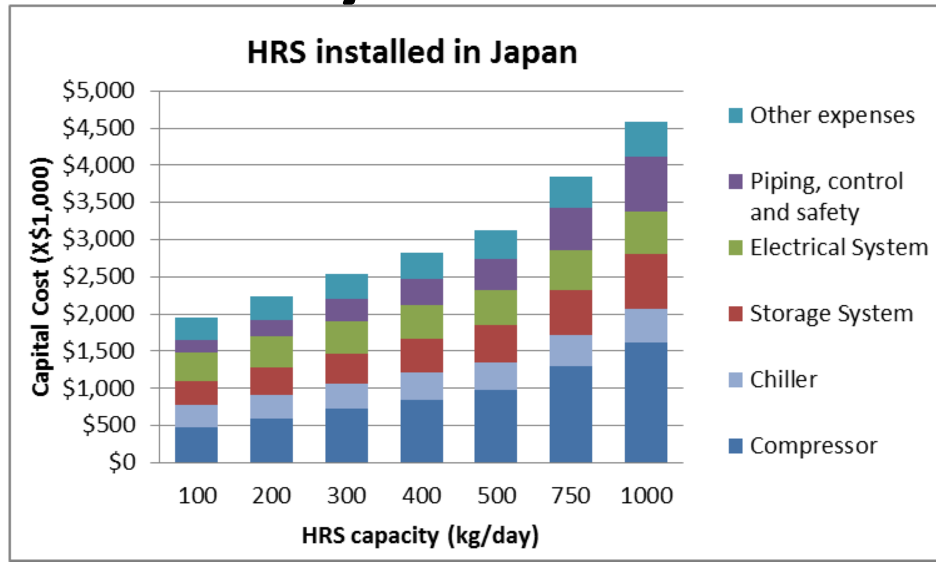


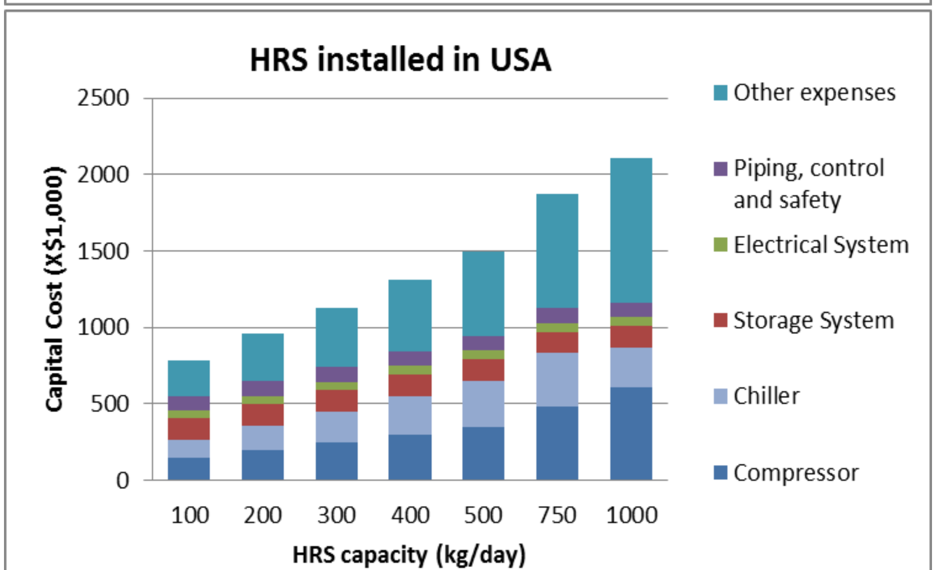


Other Expenses include site engineering; permitting; commissioning; and construction

Accomplishments: Estimated Capital Cost Using Regression Analysis







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

Regression Analysis Results

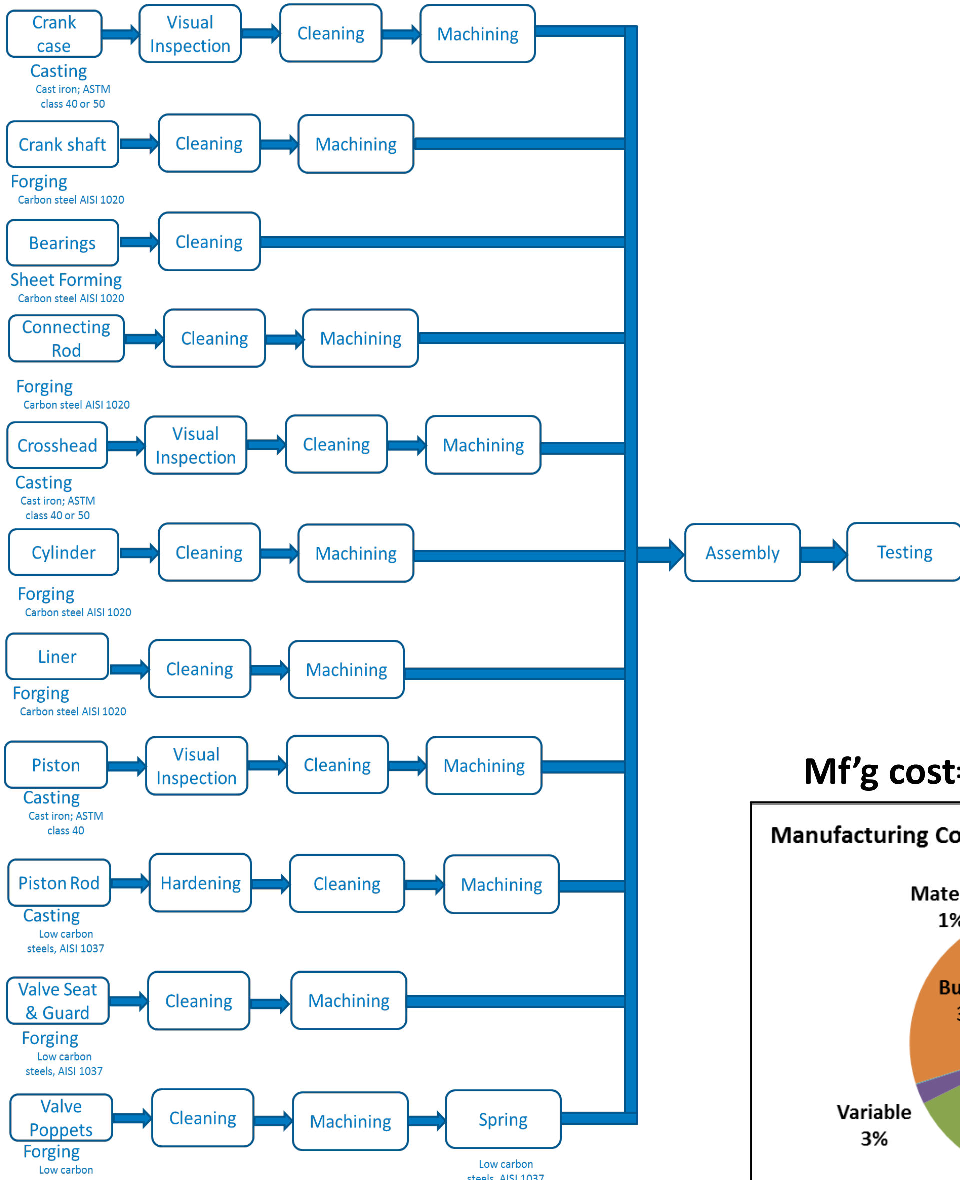
- Example 1: **100 kg/day HRS**:
  - **Regression analysis:** $1.30M in Europe; $1.95M in Japan; **$0.78M in USA**
  - HDSAM/ANL estimate: $<0.85M ($2015)
  - H2FIRST estimate : $0.97M ($2014)
  - **CEC actual (130 kg/day): $1.61M ($'14-'15)**
- Example 2: **200 kg/day HRS**:
  - **Regression analysis:** $1.5M in Europe; $2.24M in Japan; **$0.96M in USA**
  - HDSAM/ANL estimate: $1M ($2015)
  - H2FIRST estimate: $0.91M ($2014)
  - **CEC actual (180 kg/day): $1.98M ($'14-'15)**

Assumptions- Compressor Manufacturing

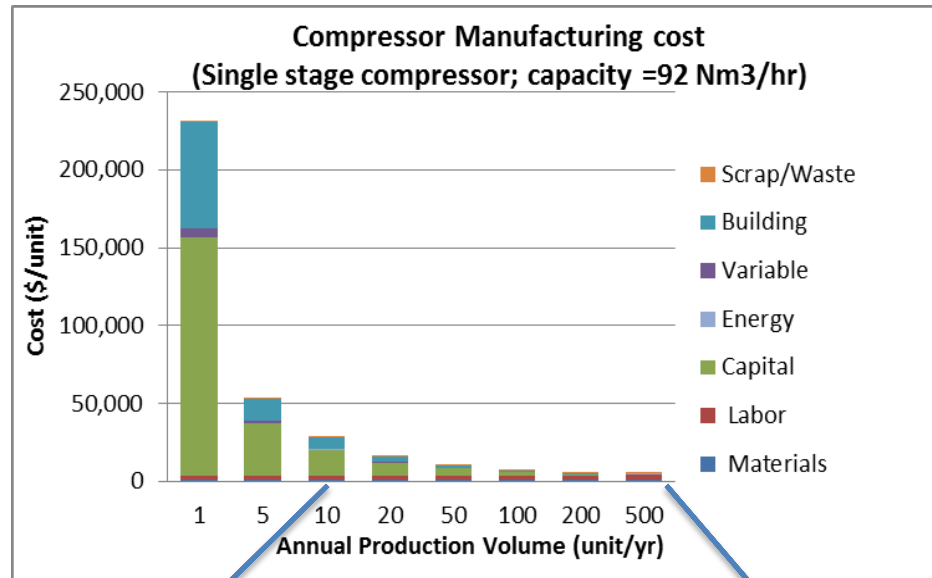
- 1 stage compressor
- Compression ratio < 6
- P_{in}= 150-200 bar; P_{out}= 350-420 bar (5,000-6,000 psi)
- Manufacturing cost model for compressor case and internal parts only
- Balance of system was added to the direct manufacturing cost of the compressor case &internal parts
- 30% of the direct manufacturing 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

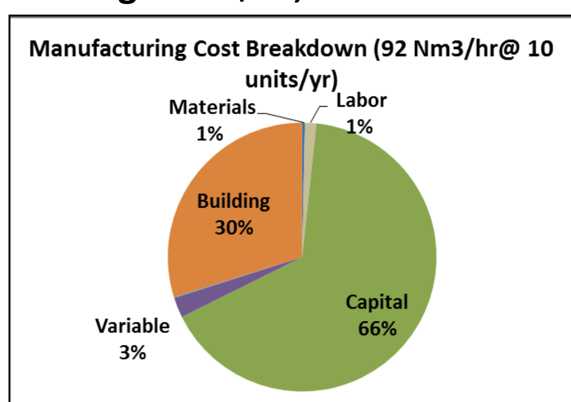
Process Flow- Piston Compressor- 1 stage



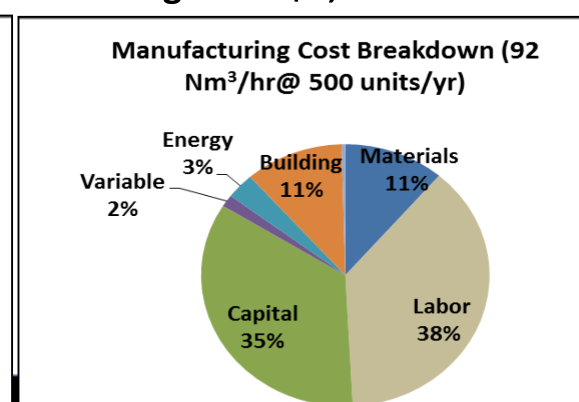
While diaphragm compressors have maintenance and performance advantages over piston compressors, they are also considerably more expensive*



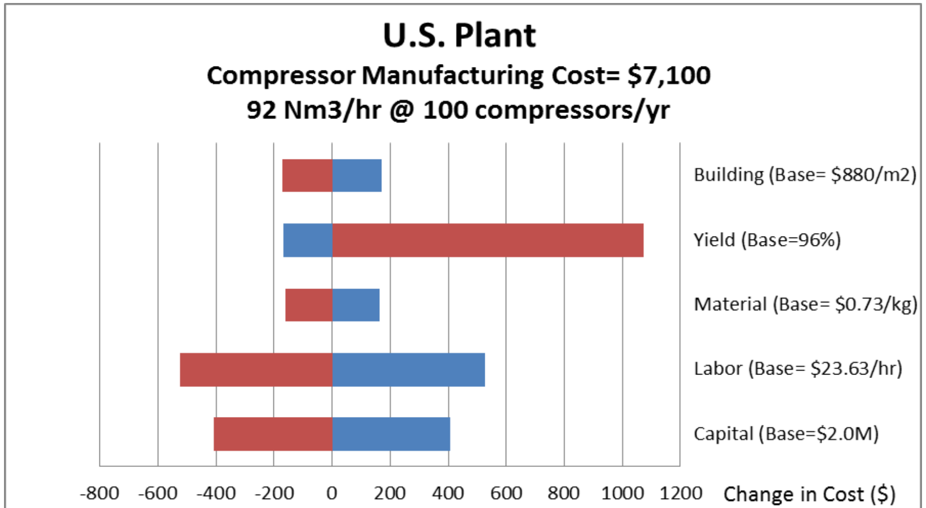
Mf'g cost=$28,450



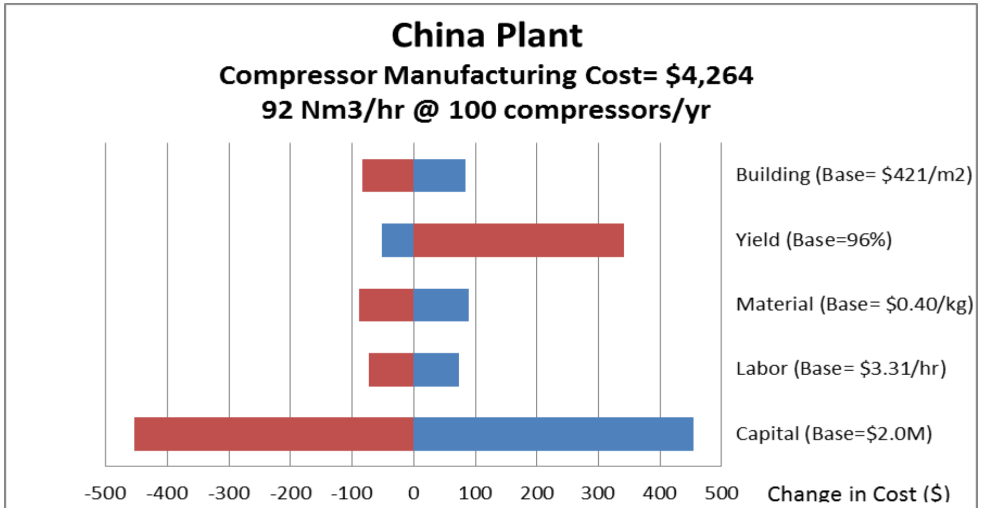
Mf'g cost= $5,150



Accomplishment: Sensitivity Analysis- H_2 Compressor Housing and Internal Parts



	Capital (Base=$2.0M)	Labor (Base= $23.63/hr)	Material (Base= $0.73/kg)	Yield (Base=96%)	Building (Base= $880/m2)
+20%	$407	$525	$162	-$169	$172
-20%	-$407	-$525	-$162	$1,074	-$172



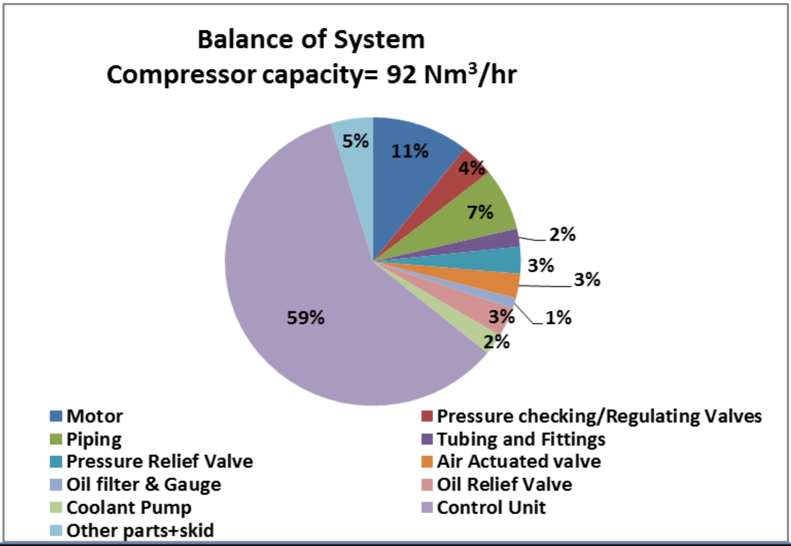
	Capital (Base=$2.0M)	Labor (Base= $3.31/hr)	Material (Base= $0.40/kg)	Yield (Base=96%)	Building (Base= $421/m2)
+20%	$454	$74	$89	-$51	$83
-20%	-$454	-$74	-$89	$341	-$83

- **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**

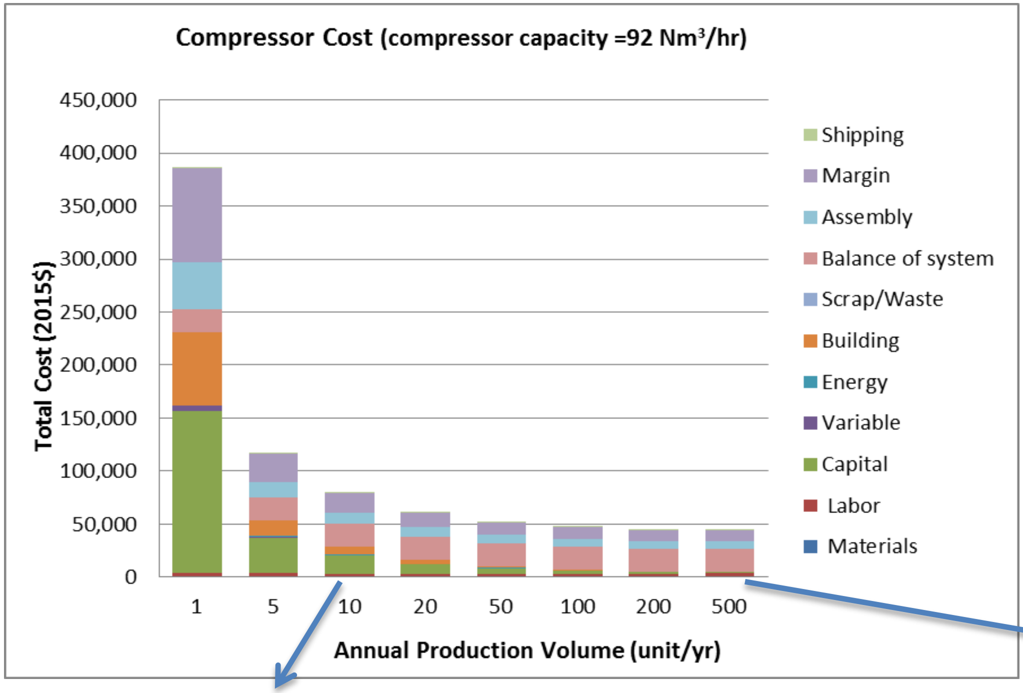
Accomplishment: Compressor Balance of System Cost Analysis

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

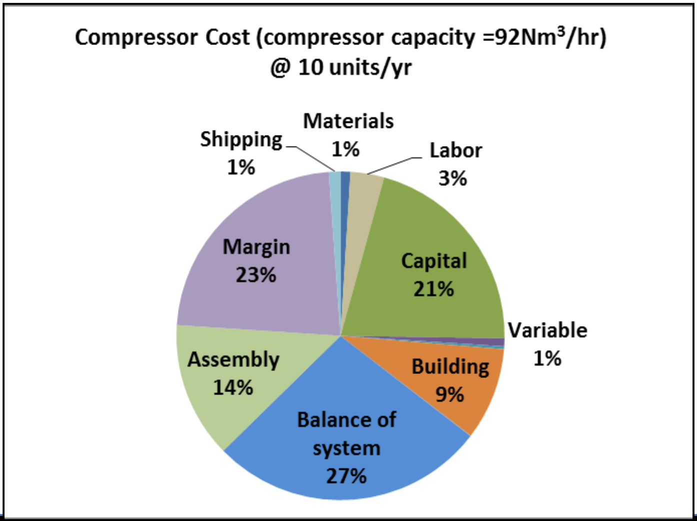
- Motor cost estimated based on price of commercial industrial motors
- Control Unit shares about 59% of the total BOS parts cost.
- Total BOS cost= $21,076
- Discounts for high quantities can reduce BOS cost
- Assembly cost in U.S. plant =$7,100 (~300 man-hour; Avg. wages $23.63/hr)



Accomplishment: Hydrogen Compressor- Minimum Sustainable Price

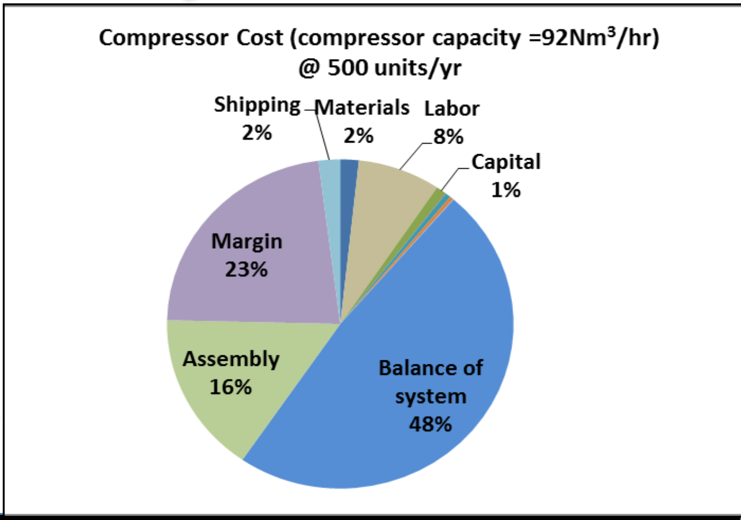


- Compressor capacity= 92 Nm^3/hr or 200 kg/day (1 stage)
- P_{in}= 150-200 bar; P_{out}= 350-420 bar
- Shipping cost is assumed for shipping compressors from East Coast to West Coast in this example
- Margin is assumed to be 30% of the manufacturing cost

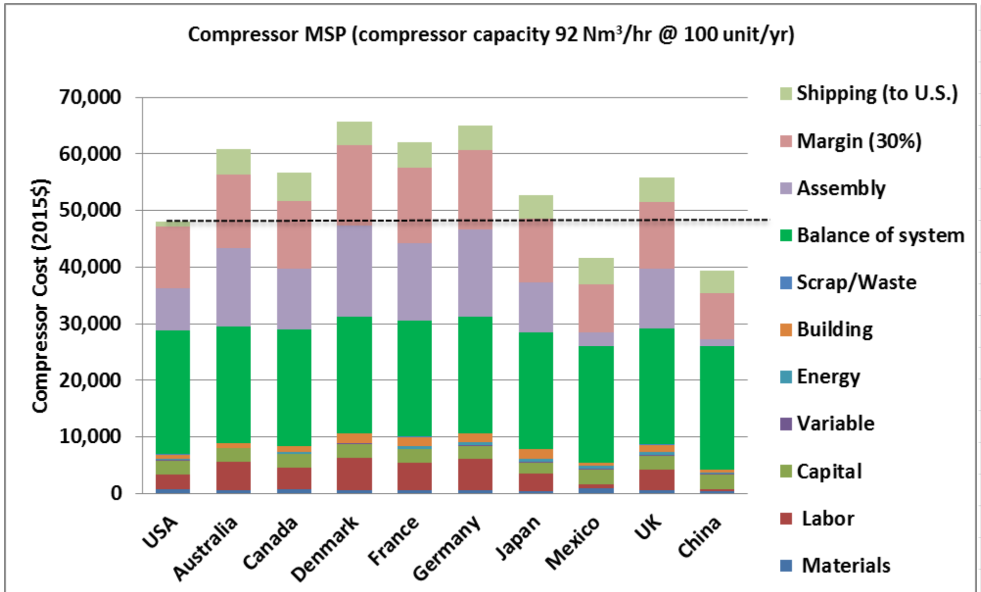


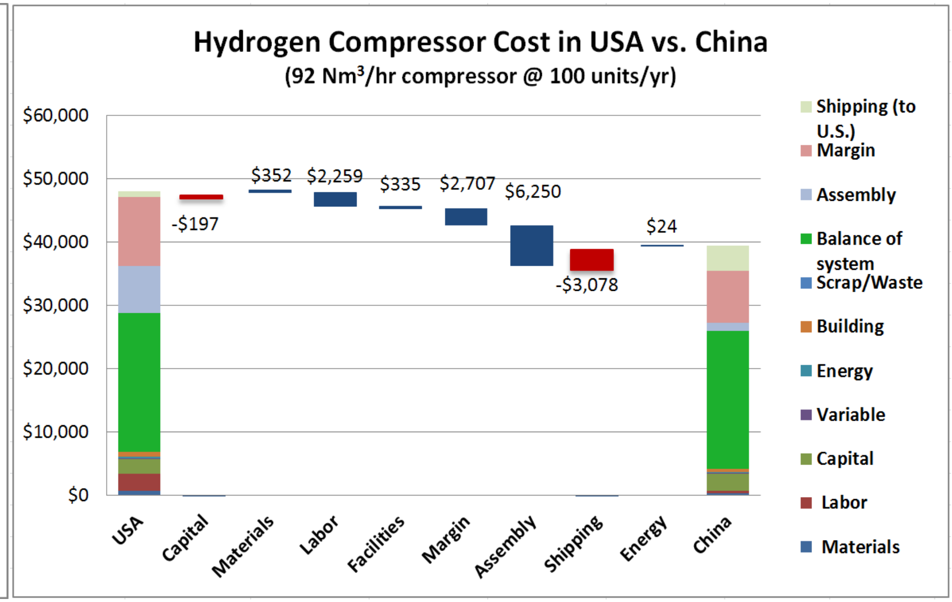
Mf'g cost=$80,268

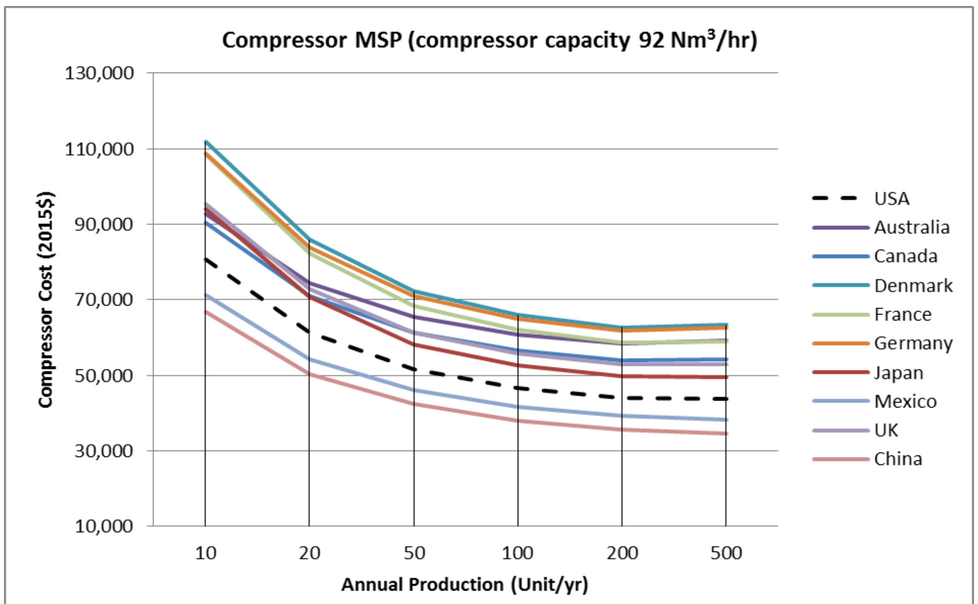
Mf'g cost= $43,340



Accomplishment: Minimum Sustainable Price



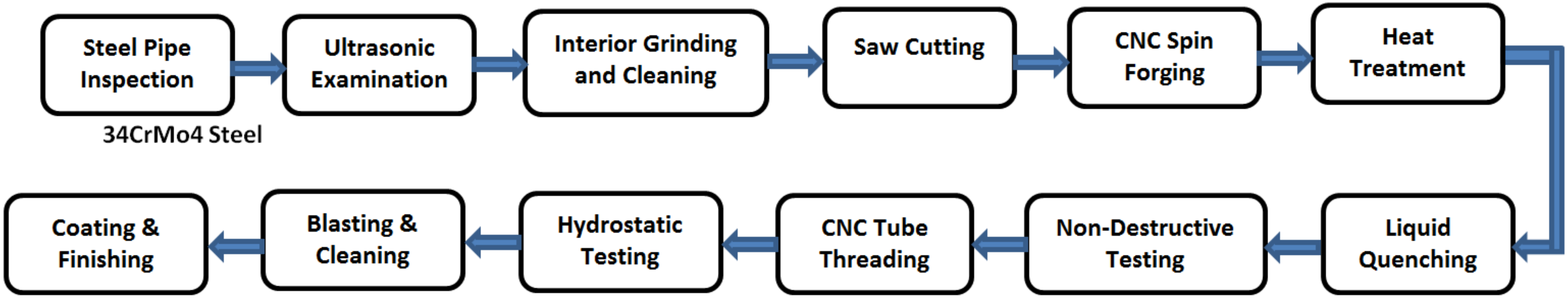




- United States advantages are lower shipping and interest rates and longer experience in this field
- China's advantage relative to the U.S. is driven by lower labor, low material cost, building and energy costs
- Mexico's advantage relative to the U.S. is driven by lower labor, and building costs

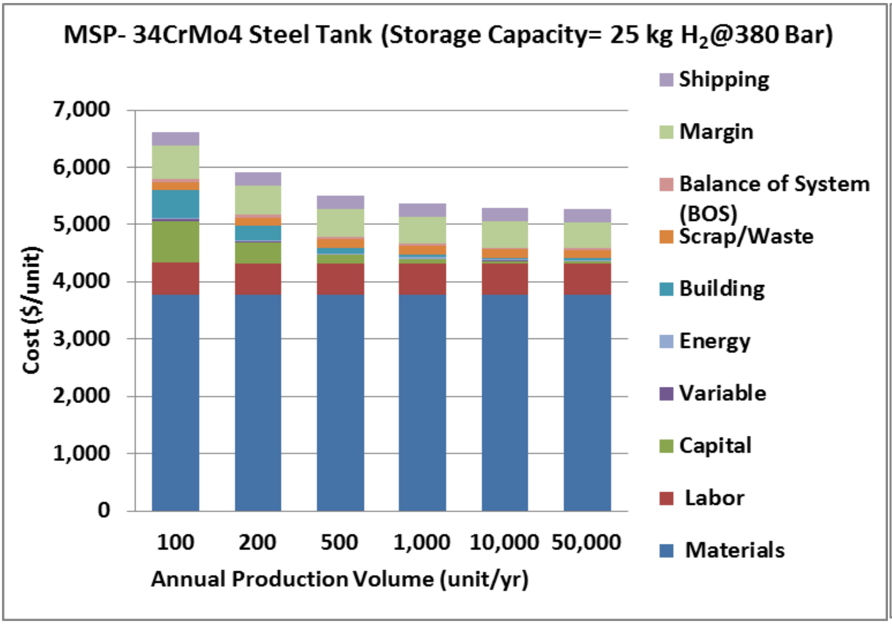
Accomplishment: Seamless Metal H_2 Vessels (Type I)

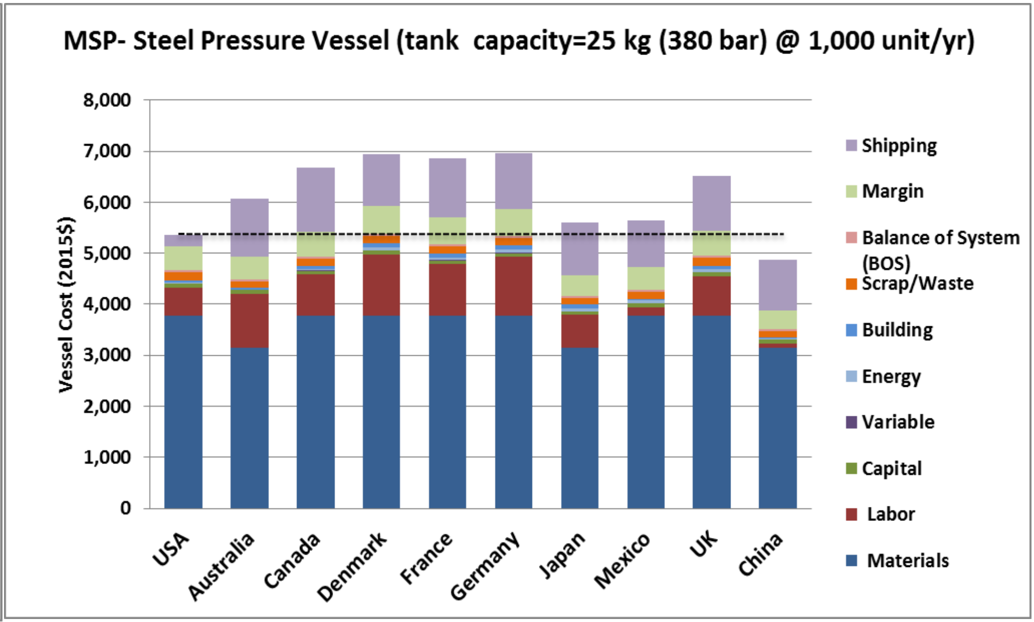
Process Flow- Type 1 Steel Tanks



Manufacturing Cost Curve (U.S. Plant)

Minimum Sustainable Price





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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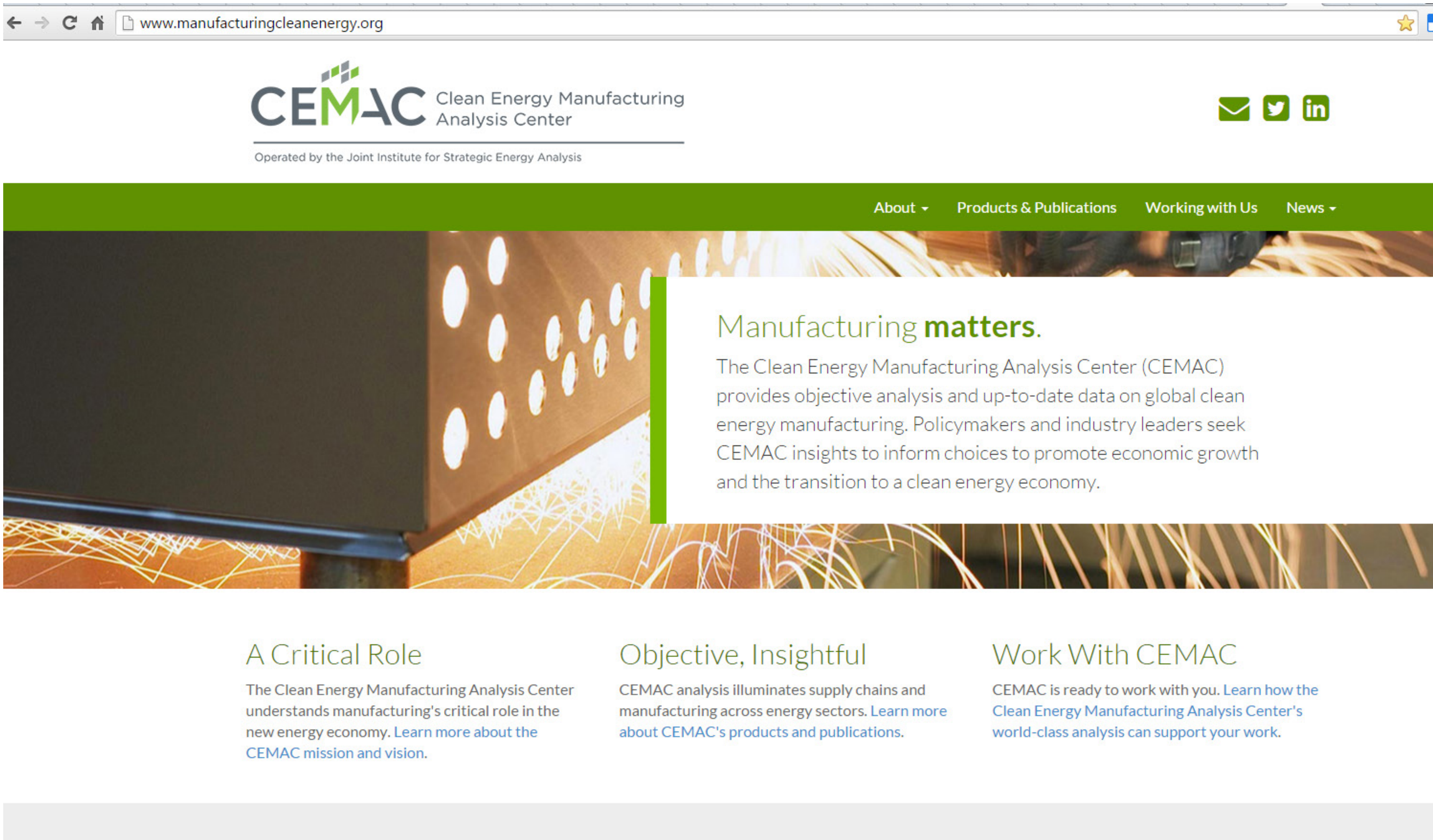
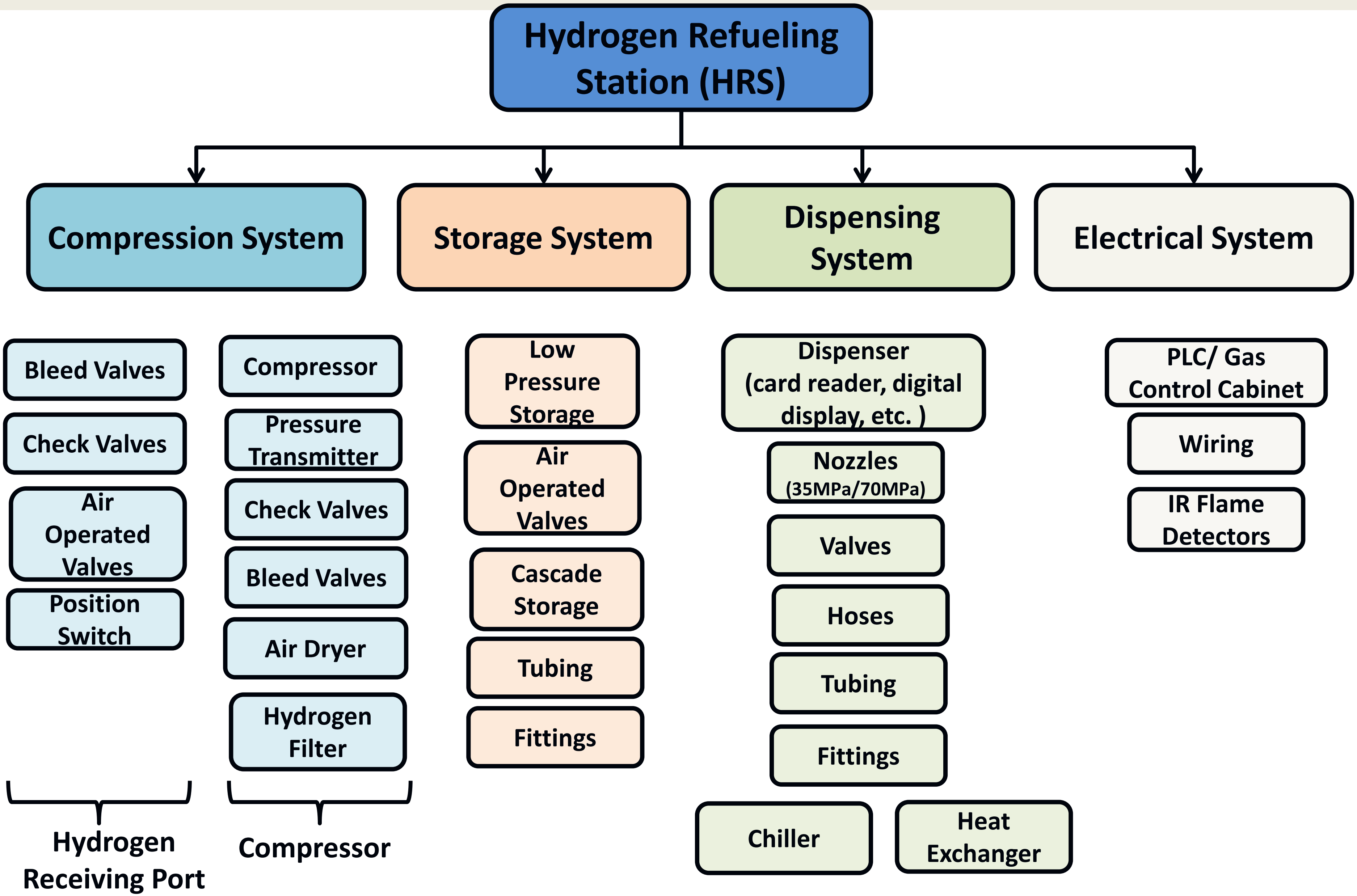


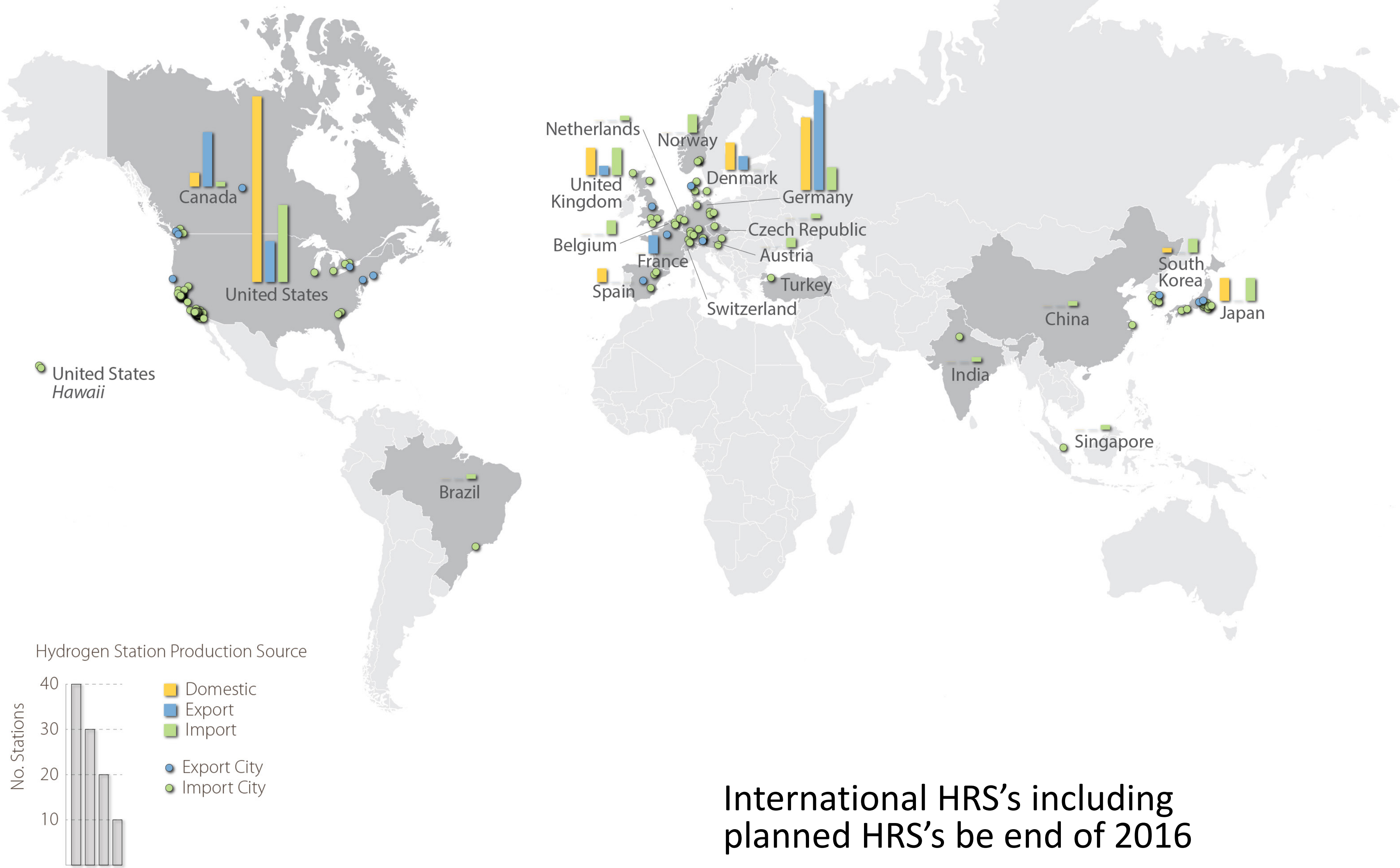
Backup Slides

Approach: Gaseous HRS Components



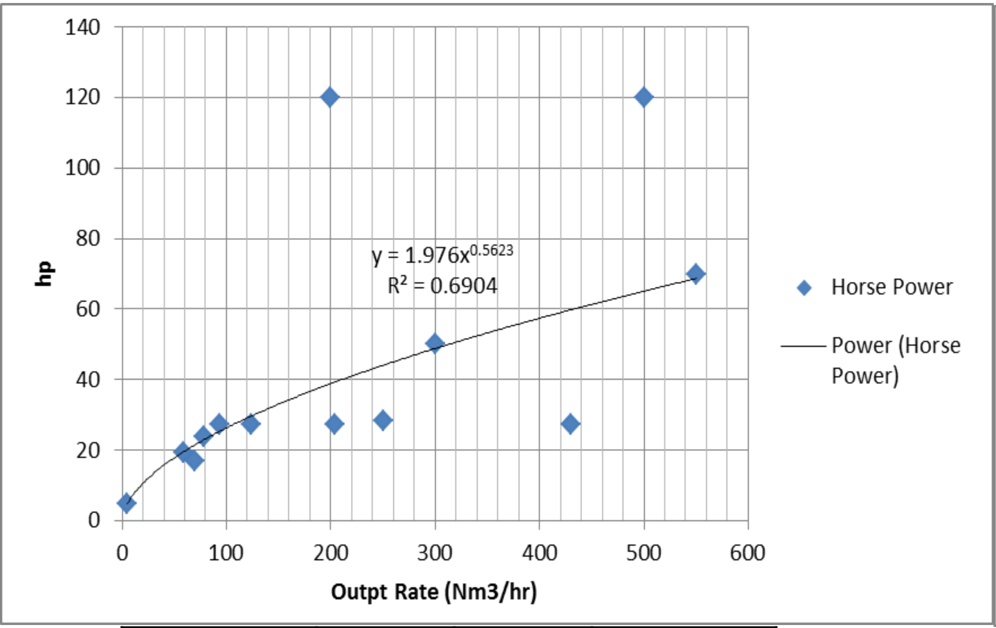
Accomplishments: HRS Flow Map

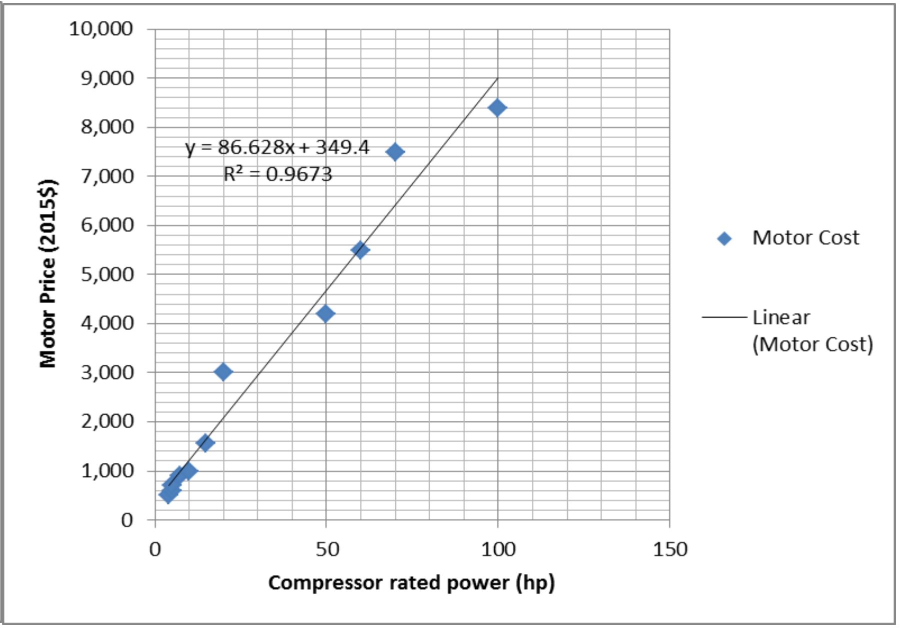
Number of HRS's; medium to high capacities (>50 kg/day)



International HRS's including planned HRS's be end of 2016

Compressor Motor Cost Analysis



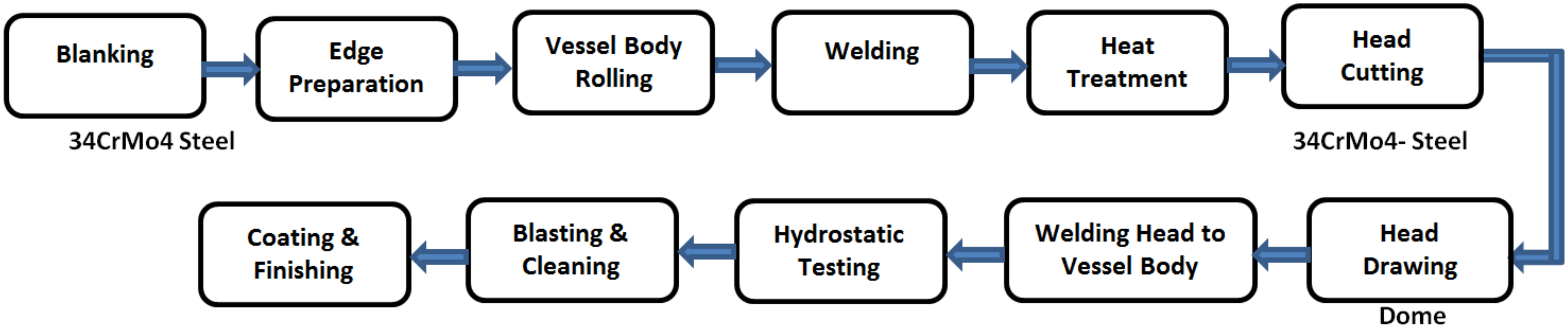


Manufacturer	kg/day	Nm3/hr	Horse Power
PDC Machines	431.4	200.0	120
PDC Machines	10.8	5.0	5
Hofer	647.1	300.0	50
Hofer	1186.4	550.0	70
Hofer	1078.6	500.0	120
Haskel	540.6	250.6	28.5
Haskel	150.0	69.6	16.9
Haskel	200.7	93.1	27.4
Haskel	926.8	429.7	27.2
Haskel	127.2	59.0	19.3
Haskel	168.1	77.9	24
Haskel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

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

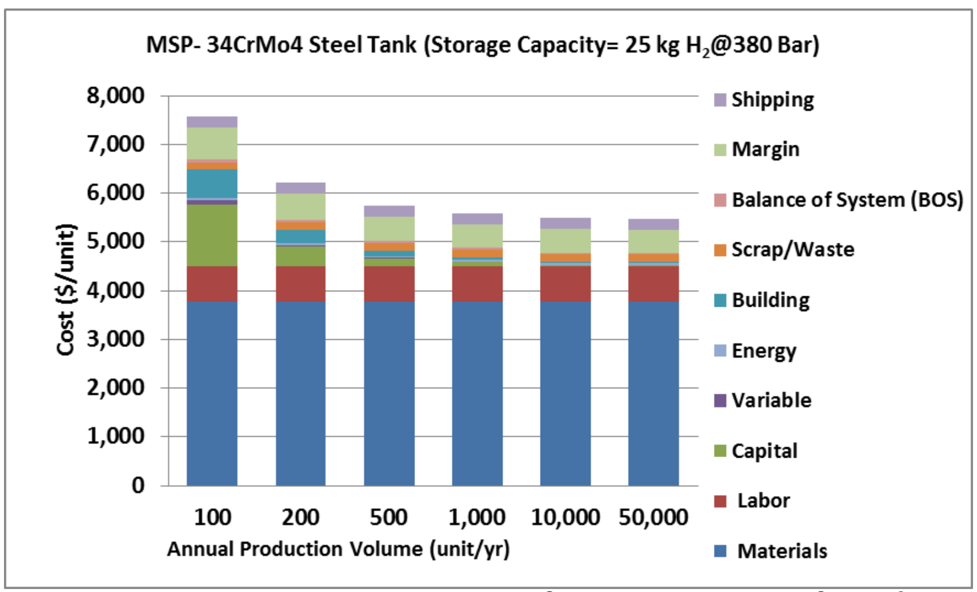
Welded Metal H_2 Vessels (Type I)

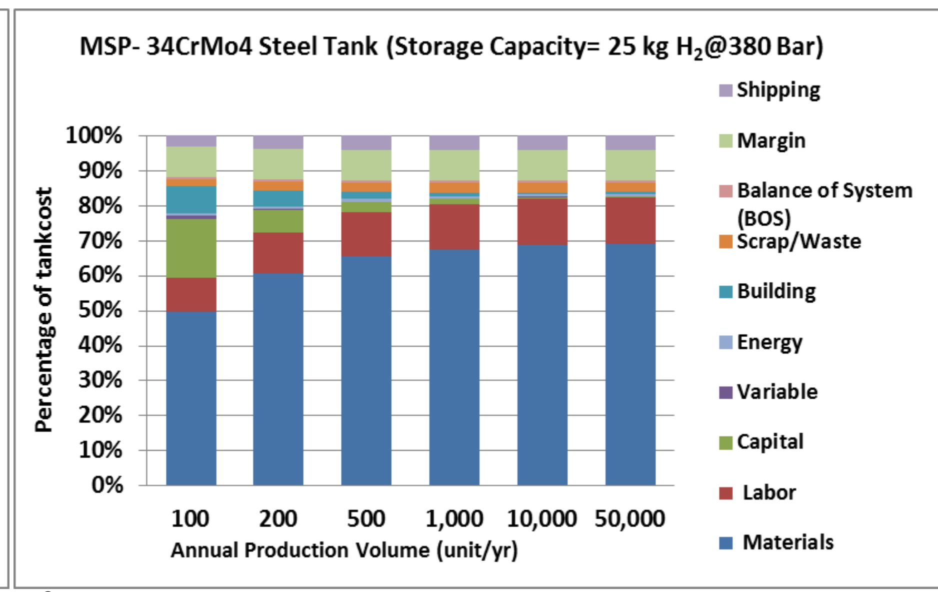
Process Flow- Type 1 Steel Tanks



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