Manufacturing Competitiveness Analysis for Hydrogen Refueling Stations and Electrolyzers

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DOE Hydrogen and Fuel Cells Program
2018 Annual Merit Review and Peer Evaluation Meeting

Project ID # MN017

Overview

Timeline

- Project start date: April 2015
- Project end date: June 2018
- Percent complete: 90%

Technical Barriers

Cross-Cutting Fuel Cell Barriers

- F. Manual Stack Assembly
- I. Lack of Standardized Balance-of-Plant Component

Hydrogen Generation by Water Electrolysis

- F. Capital Cost
- K. Manufacturing

Budget

- Total project funding
  - DOE share: $719 K
  - Contractor share: n.a.
- Funding received in FY18: $0

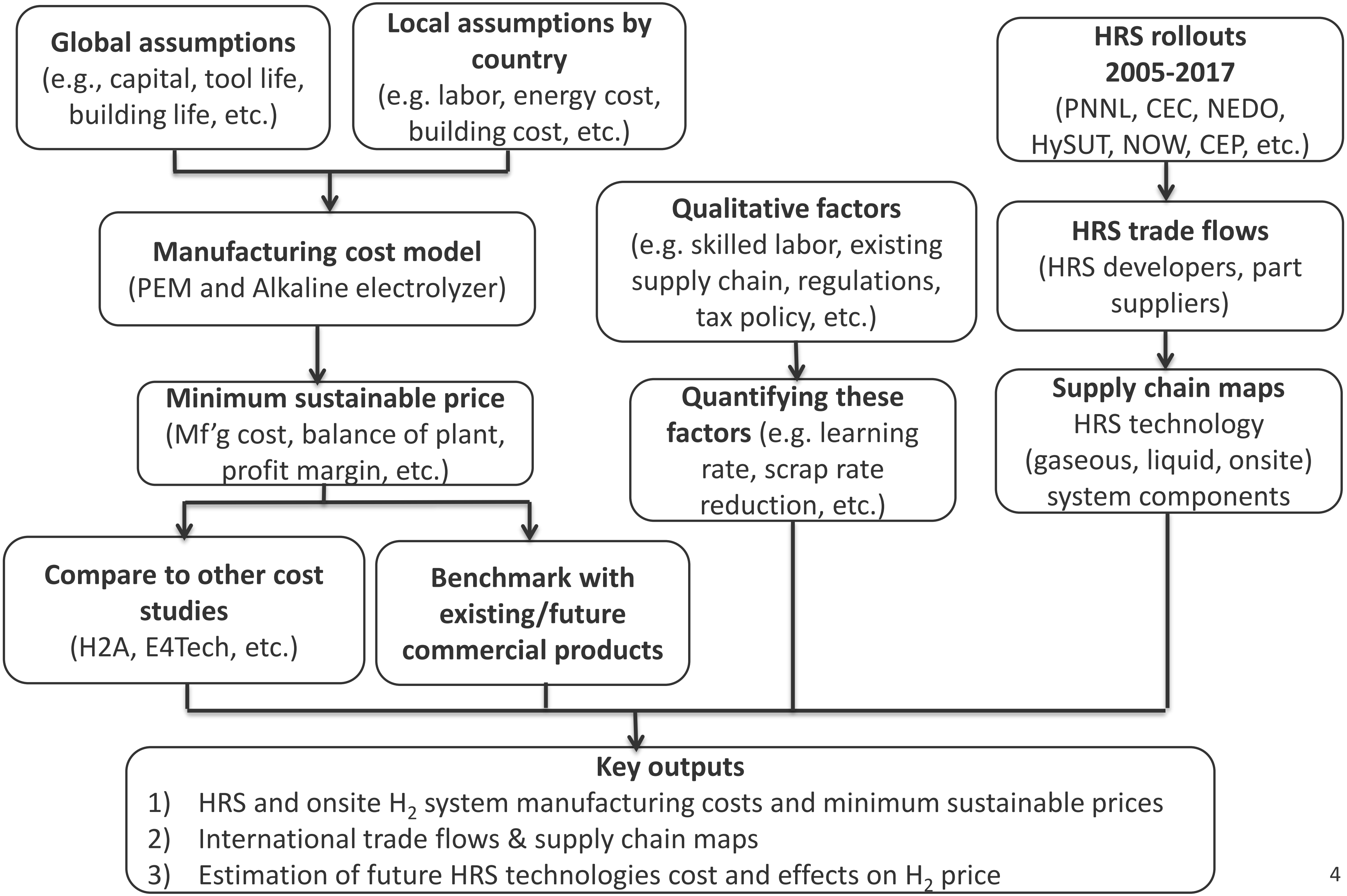
Collaborators

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

Relevance & Goals

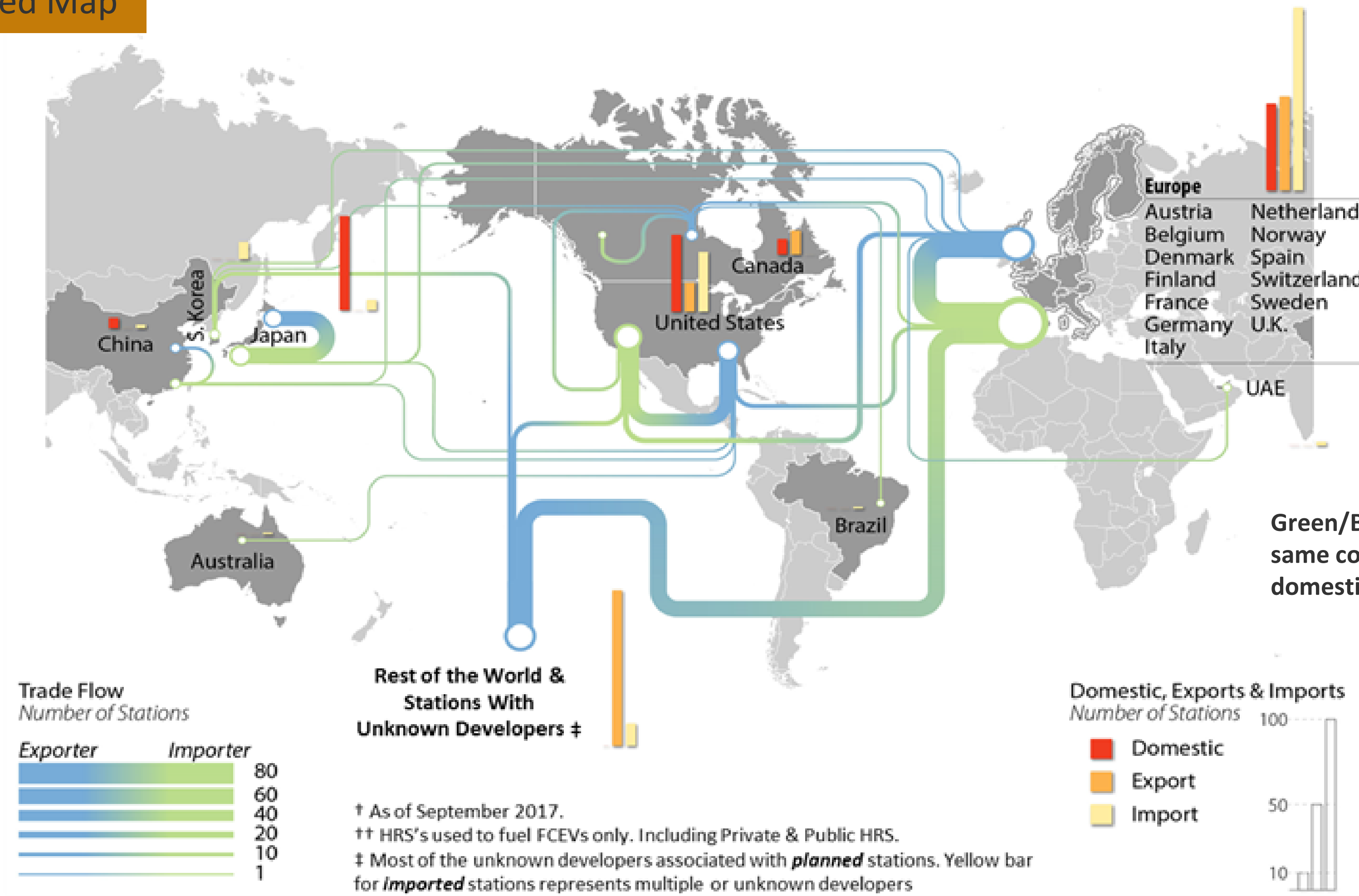
- To develop detailed bottom-up manufacturing cost analysis for key systems/parts in the hydrogen refueling station (HRS).
- To identify cost drivers for key systems in the hydrogen refueling stations (e.g., compressors, storage tanks, dispenser, coolers and heat exchanger)
- To identify cost drivers for onsite hydrogen production systems (PEM and alkaline electrolyzers)
- To investigate effect of economies of scale and learning experience on the cost of the onsite hydrogen production systems

Approach


Global assumptions
(e.g., capital, tool life, building life, etc.)
Local assumptions by country
(e.g. labor, energy cost, building cost, etc.)
HRS rollouts 2005-2017
(PNNL, CEC, NEDO, HySUT, NOW, CEP, etc.)
Manufacturing cost model
(PEM and Alkaline electrolyzer)
Qualitative factors
(e.g. skilled labor, existing supply chain, regulations, tax policy, etc.)
HRS trade flows
(HRS developers, part suppliers)
Minimum sustainable price
(Mf'g cost, balance of plant, profit margin, etc.)
Quantifying these factors (e.g. learning rate, scrap rate reduction, etc.)
Supply chain maps
HRS technology (gaseous, liquid, onsite) system components
Compare to other cost studies
(H2A, E4Tech, etc.)
Benchmark with existing/future commercial products
Key outputs
1) HRS and onsite H_2 system manufacturing costs and minimum sustainable prices
2) International trade flows & supply chain maps
3) Estimation of future HRS technologies cost and effects on H_2 price

Accomplishment- Global HRS Trade Flows

Updated Map



Green/Blue colors within same country represent domestic shipments only

Source of data:
PNNL 09/2017,
Alternative fuel data center, 2 017

NREL analysis 2017

United States		Japan		Germany		United Kingdom		France		Denmark		Norway		Other Western Europe Countries		Rest of the World	
Active	Planned	Active	Planned	Active	Planned	Active	Planned	Active	Planned	Active	Planned	Active	Planned	Active	Planned	Active	Planned
62	18	92	3	38	37	11	13	4	5	10	1	7	5	31	6	22	13
78%	23%	97%	3%	51%	49%	46%	54%	44%	56%	91%	9%	58%	42%	84%	16%	63%	37%

Comparison Between PEM And Alkaline Electrolyzers

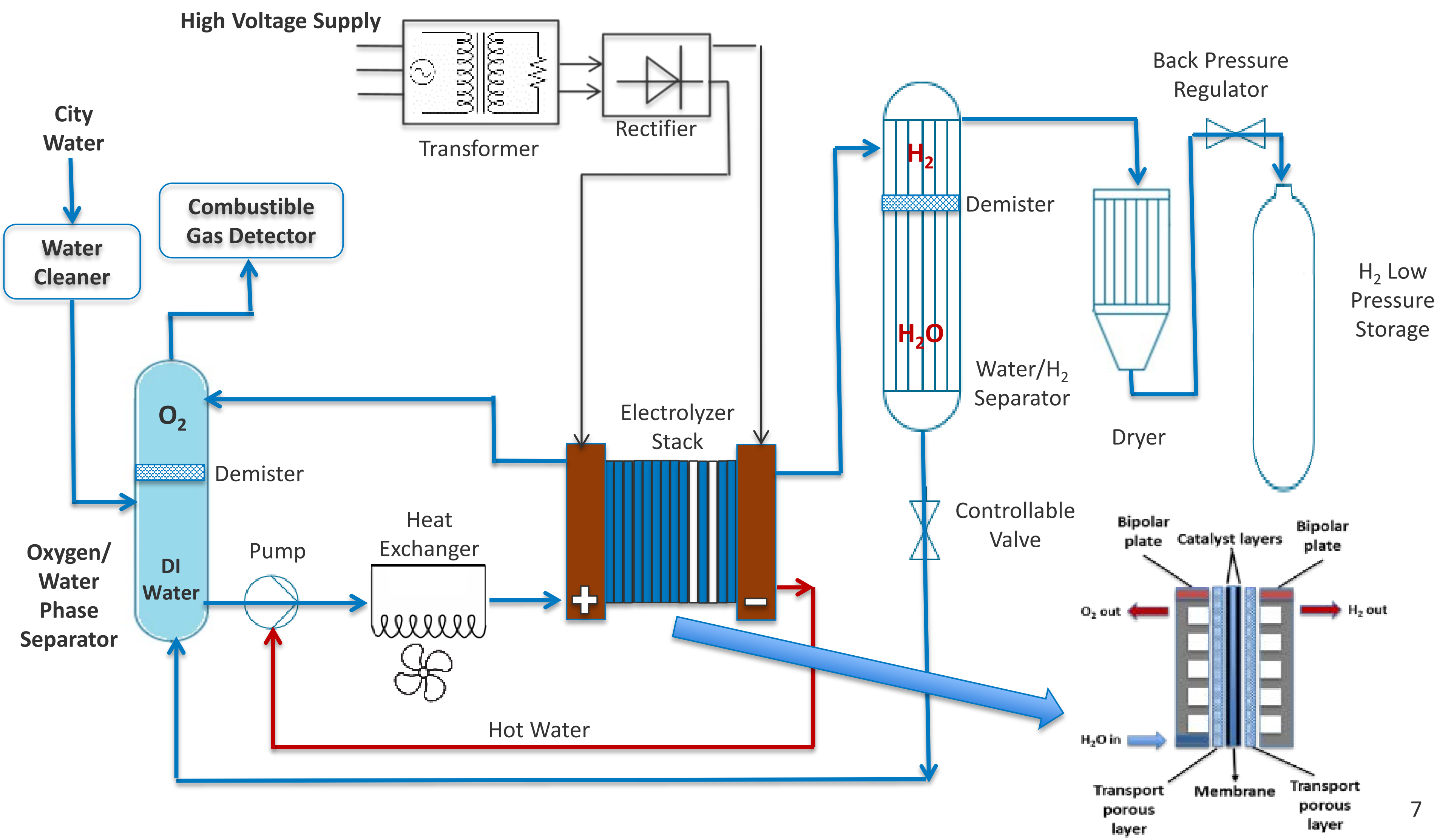
PEM electrolyzers have larger current and power densities, shorter startup time and higher system price (in $/kW)

Characteristics	Alkaline	PEM	Unit	Notes
Current Density	0.2 - 0.7	1.0 - 2.2	A/cm^2	
Power Density	0.32 - 1.12	1.4 – 3.52	W/cm^2	Reference voltage = 1.6 volt
Operating Temperature	60 – 80	50 – 84	°C	
Electricity Consumption (Median)	50 – 73 (53)	47 – 73 (52)	kWh/kg-H_2	Electrolysis system only. Excluding storage, compression and dispensing
Min. Load	20 - 40%	3 – 10%		
Startup Time from Cold to Min. Load	20 min - 60+	5 – 15	minutes	
System Efficiency (LHV) (Median)	45-67% (63%)	45 – 71% (63%)		
System Lifetime (Median)	20-30 (26)	10-30 (22)	Year	
System Price	$760 – $1,100 ($930)	$1,200-$1,940 ($1,570)		Including power supply, system control and gas drying. Excluding grid connection, external compression, external purification and H_2 storage

Sources of data: Bertuccioli et al., 2014, NREL analysis 2017

PEM Electrolyzer System Design

Stack is the core of the PEM electrolysis system. Balance of plant parts usually outsourced from reliable vendors



Accomplishment- PEM Electrolyzer Functional Specifications for Analysis

Current and power densities are key parameters in the cell design

Stack Power	10	20	50	100	200	500	1,000	2,000	5,000	10,000	kW
single cell amps	1224										A
current density	1.80										A/cm^2
reference voltage	1.619										V
power density	2.913										W/cm^2
Pt-Ir loading- Anode	7.0										g/m^2
PGM loading Cathode	4.0										g/m^2
single cell power	1981.0										W
Cells per system	5	10	25	50	101	252	505	1010	2524	5048	cells
stacks per system	1	1	1	1	1	1	2	4	10	20	stacks
cells per stack	5	10	25	50	101	252	252	252	252	252	cells

Current density and reference voltage were estimated using average values for several commercial PEM electrolyzers

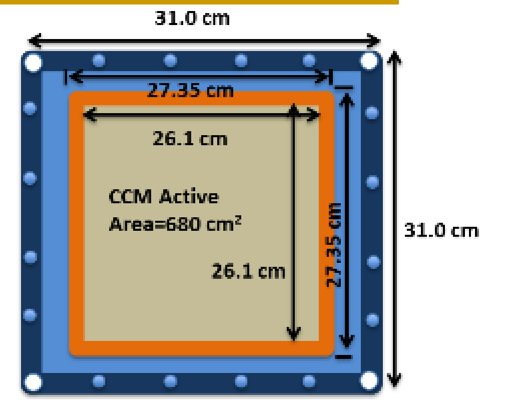


Plate area= 957 cm²

Part	Assumptions	Notes
Membrane	Nafion 117 (Purchased)	PFSA (PEEK, PBI)
Pt	Pt-price= $1500/tr.oz	DOE current value
CCM	Spray Coating	Platinum loadings: Anode= $7 g/m^2$ (Pt) Cathode= $4 g/m^2$ (Pt-Ir)
Porous Transport Layer	Sintered porous titanium Ti-price= $4.5/kg	Porosity=30%
Seal/Frame	Screen printed PPS-40GF or PEEK seal	Seal: 0.635 cm from each side for MEA bonding
Plates	Stamped stainless steel 316L	Coated plates (plasma Nitriding)

PPS-40GF: poly Phenylene Sulfide (40% Glass fiber filled)

Accomplishment- Alkaline Electrolyzer Functional Specifications for Analysis

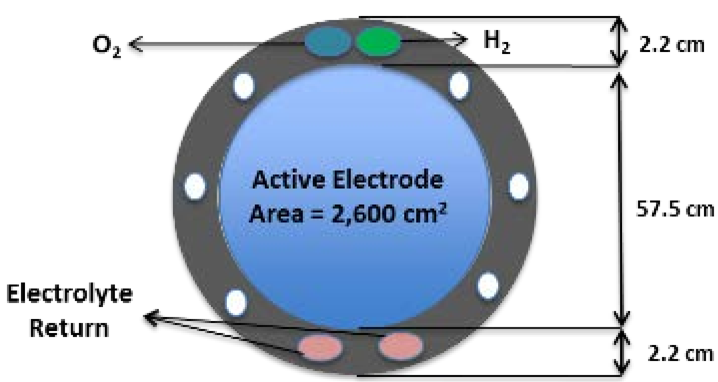
Current and power densities are key parameters in the cell design

	Stack power	10	20	50	100	200	500	1,000	2,000	5,000	10,000	kW
Stack	Avg. H_2 production rate	2	4	10	15	22	56	110	220	550	1,100	Nm^3/hr
	Avg. H_2 production rate	4	9	22	32	48	120	237	475	1,187	2,373	kg/day
	Total plate area	3,000						10,000				cm^2
	Total plate solid area	400						800				cm^2
	Electrode active area	2,600						9,200				cm^2
	Electrolyte	H_2O+ 30% KOH						H_2O+ 30% KOH				cm^2
	Single cell amps	520	520	520	520	520	520	1840	1840	1840	1840	A
	Current density	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	A/cm^2
	Reference voltage	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	V
	Power density	0.336	0.336	0.336	0.336	0.336	0.336	0.336	0.336	0.336	0.336	W/cm^2
	Single cell power	873.6	873.6	873.6	873.6	873.6	873.6	3091.2	3091.2	3091.2	3091.2	W
	Cells per system	12	23	58	115	229	573	324	647	1,618	3,235	cells
	Stacks per system	1	1	1	1	2	3	2	4	9	17	stacks
	cells per stack	12	23	58	115	115	191	162	162	180	191	cells
Additional Parasitic	Air blower/ Liquid pump	0.3	0.5	1.5	2	3	7	10	15	30	50	kW
	Other paras. loads	0.2	0.3	0.5	1	1.5	3	5	8	10	15	kW
	Parasitic loss	0.50	0.80	2.00	3.00	4.50	10.00	15.00	23.00	40.00	65.00	kW

- **Commercial alkaline electrolyzers can have large cells (~1.6m in diameter†)**
- **Electrolyte solution (Water+30% KOH)**

† See Vogt et al., 2014

Functional Cell Design



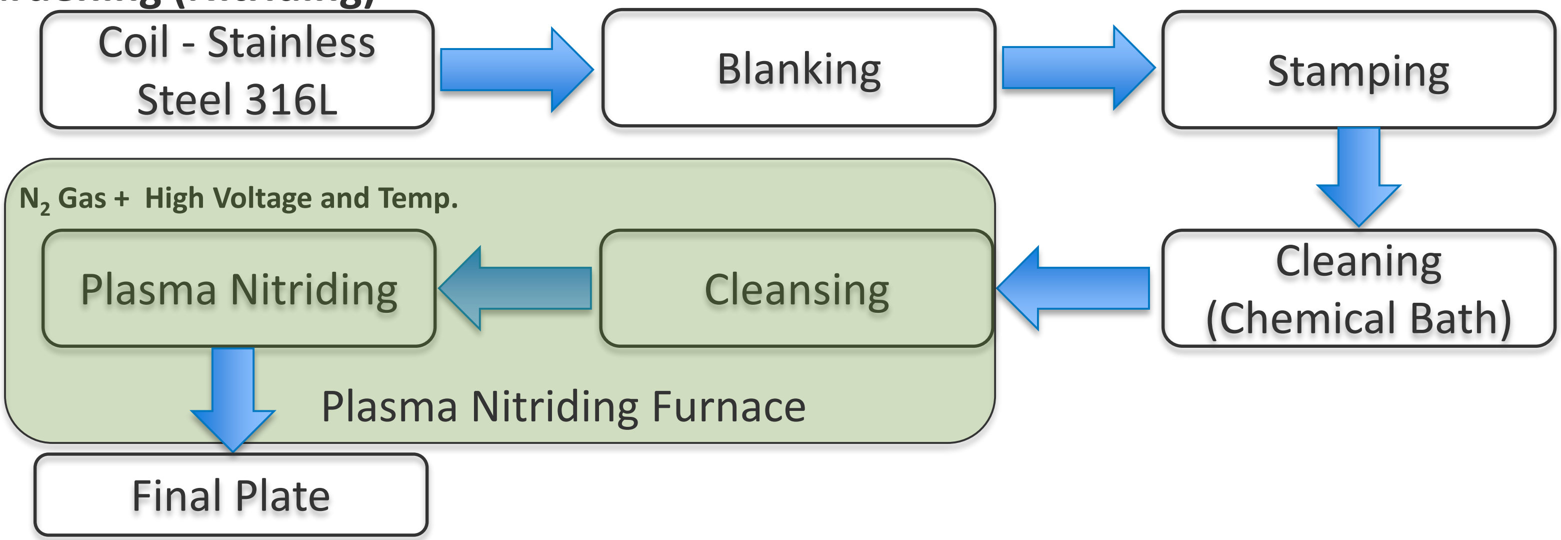
Part	Materials	Notes
Membrane	m-PBI	Cast membrane using doctor-blade machine
Electrodes	Raney-nickel	PVD + Leaching to get the required porosity
Porous Transport Layer	Pure Nickel Sheets	Corrosion resistance in alkaline solution
Frame	PPS-40GF or PEEK	Injection molding
Plates	Nickel plates	Surface treatment of high purity sheets

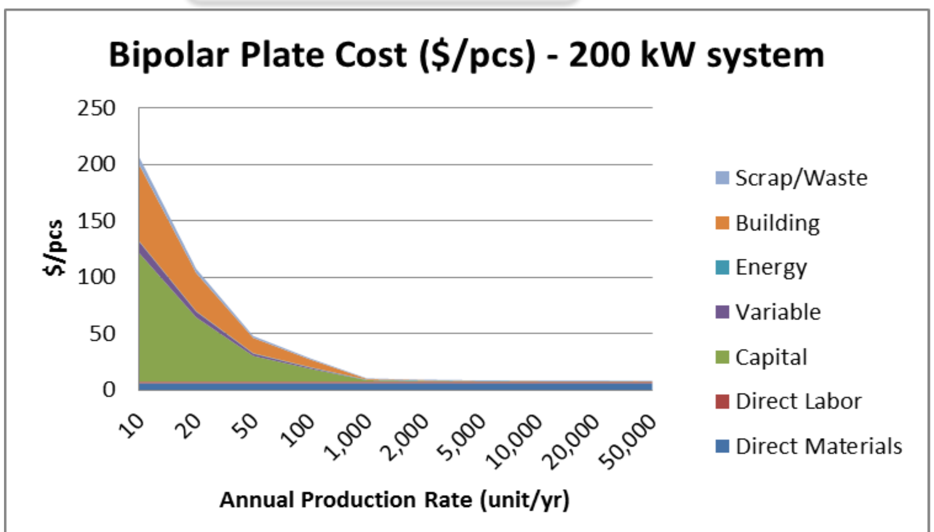
PVD: physical vapor deposition
PPS-40GF: poly Phenylene Sulfide (40% Glass fiber filled)

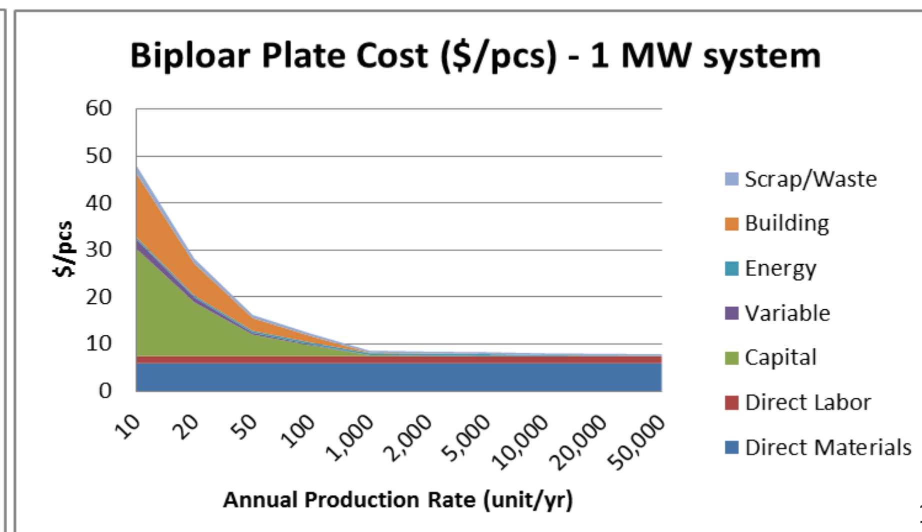
Accomplishment- PEM - Bipolar Plate Cost Model

Nitriding or other special coating processes used to improve durability of bipolar plates in acidic environment

Case Hardening (Nitriding)







Accomplishment- PEM Stack Assembly Cost Model

Stack assembly is still semi-manual and there is good room for improvements (robots, flexible assembly line)

- Semi-Automatic assembly line
- 3 workers/line
- PPS-40GF Adhesive Materials for MEA
- Compression bands or tie rods
- Stainless steel 316L end plates (thickness 30 mm)

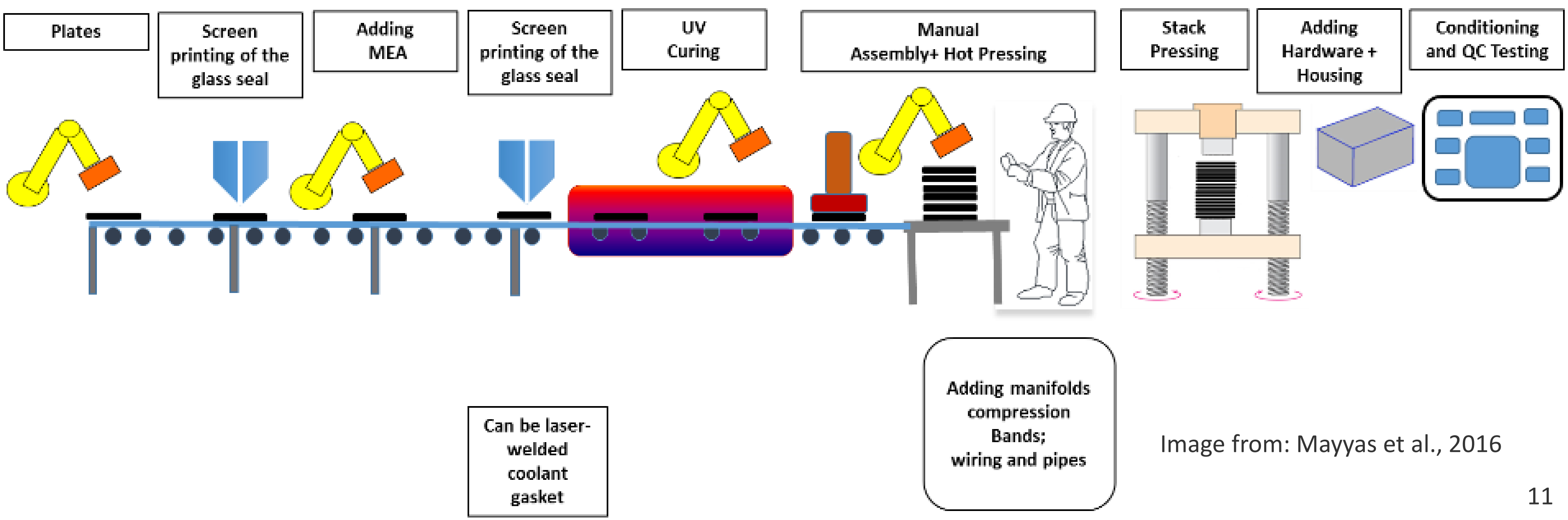
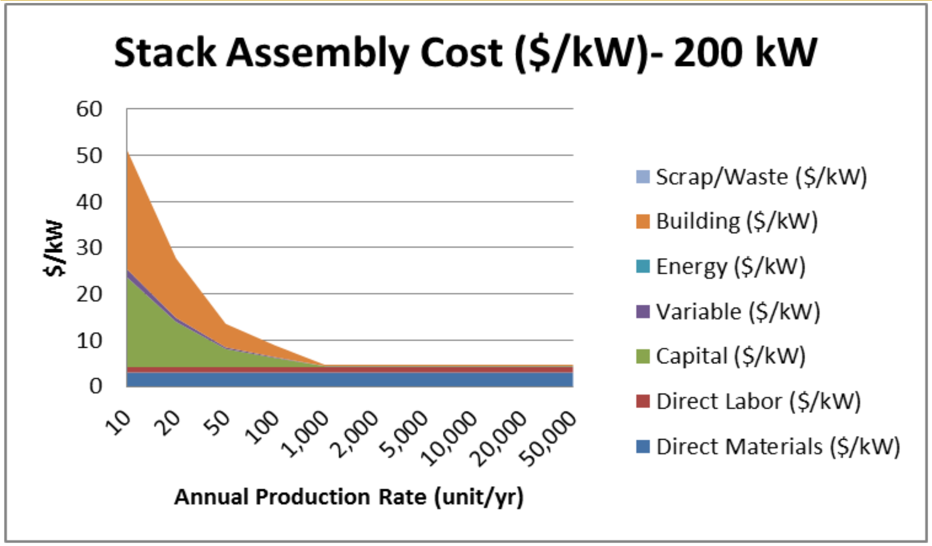
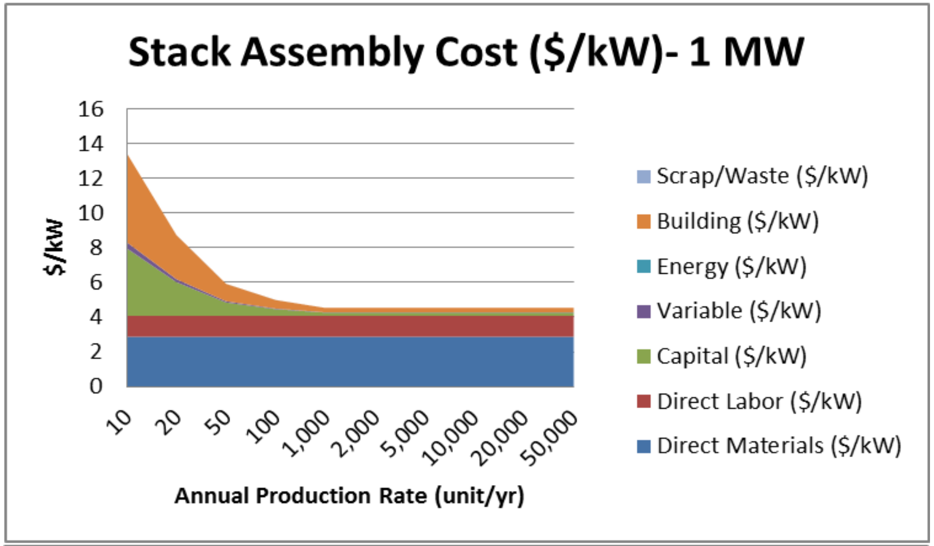


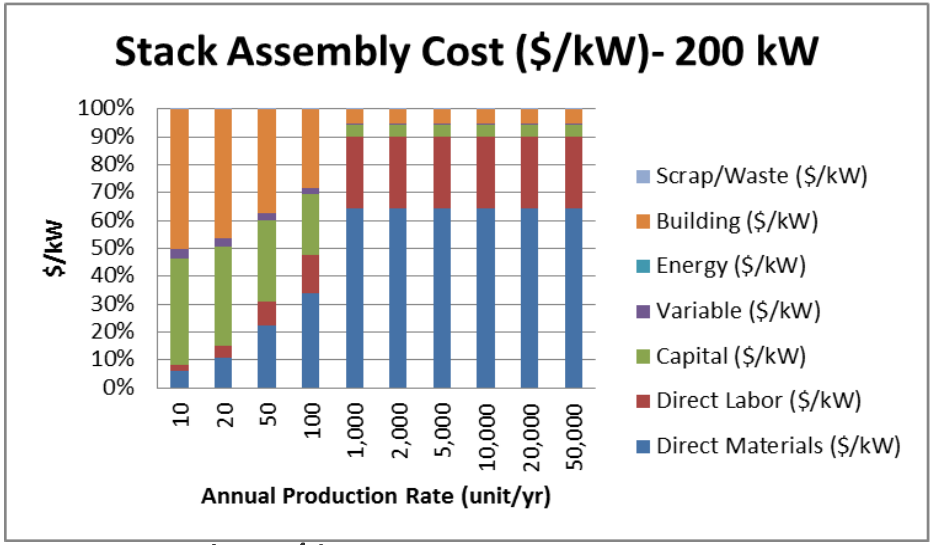
Image from: Mayyas et al., 2016

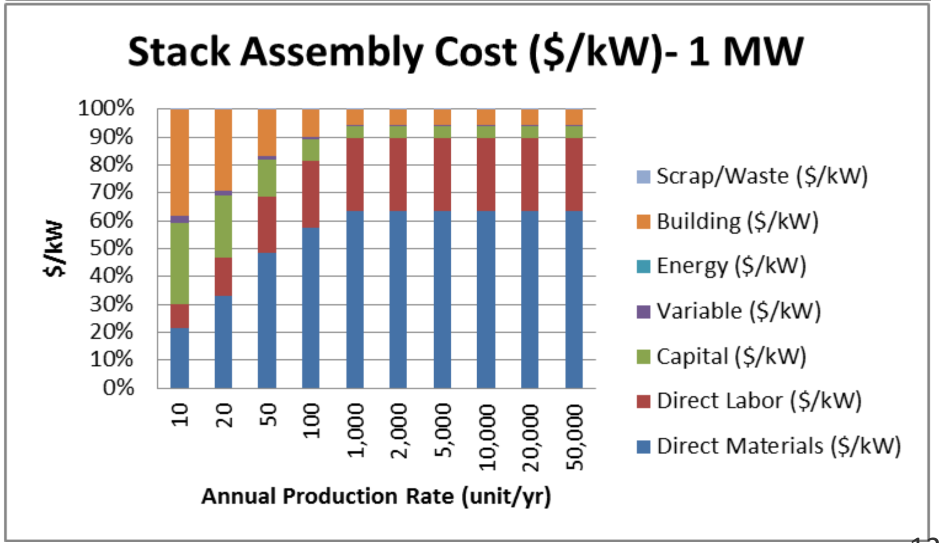
Accomplishment- PEM Stack Assembly Cost Model

Stack assembly is a labor-intensive process. Capital and building cost dominate at low production rates







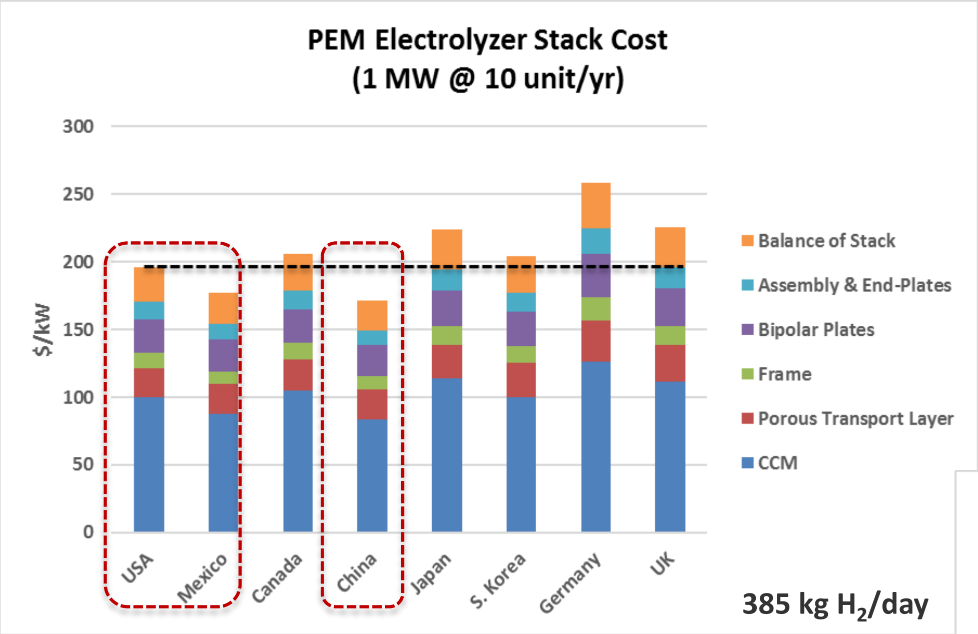


65 kg H_2/day

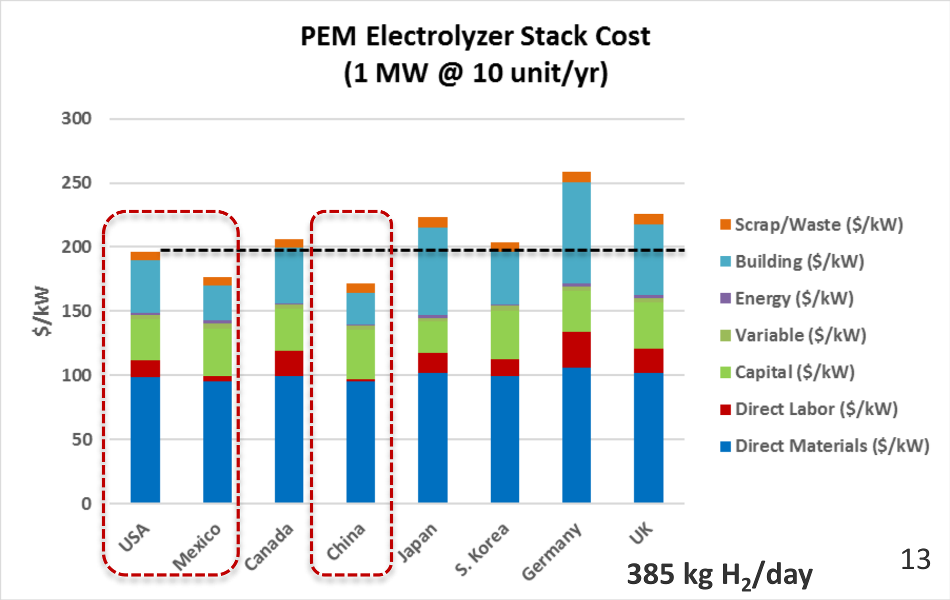
385 kg H_2/day

Accomplishment- PEM Electrolyzer Stack Cost

U.S. based manufacturers have advantages of 1) longer experience (i.e., learning rate), and 2) lower energy cost except for China and Mexico (still has smaller effect in the stack cost)

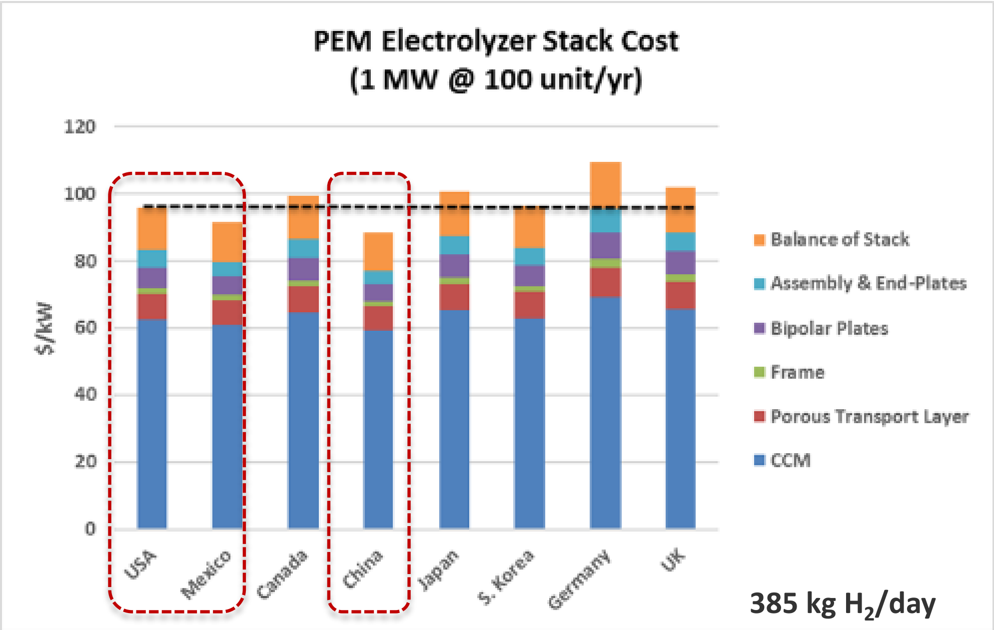


- China's advantage relative to the U.S. is driven by lower labor (including stack assembly), building, and energy costs
- Mexico's advantage relative to the U.S. is driven by lower labor (including assembly), and building costs
- Relative cost of the stack is higher in Europe because of the higher labor and energy costs
- Relative cost of the stack is higher in Japan and Canada (in relative to U.S.) because of the higher labor costs



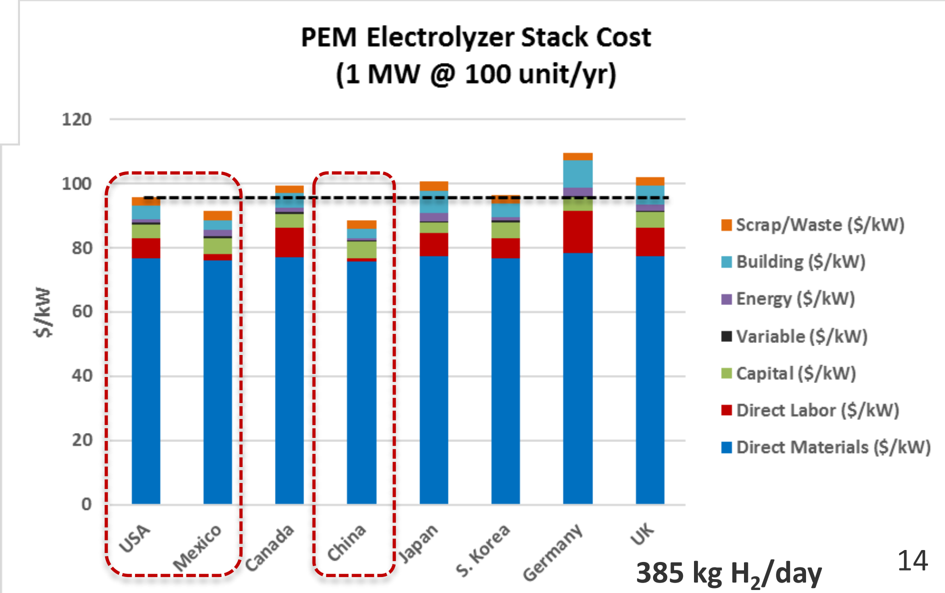
Accomplishment- PEM Electrolyzer Stack Cost

Larger production rates could also play role in reducing the cost (economies of scale for the stack modules) and balance of plant (*not shown in these charts*)

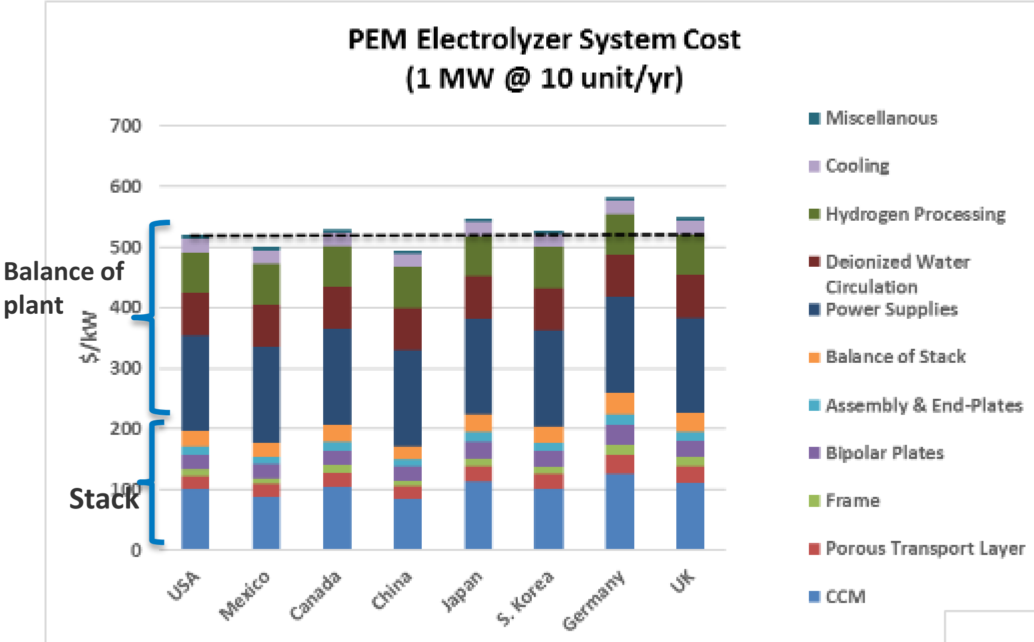


- China's advantage relative to the U.S. is driven by lower labor (including assembly), low material cost, building and energy costs
- Mexico's advantage relative to the U.S. is driven by lower labor (including assembly), and building costs

- Relative cost of the stack is higher in Europe because of the higher labor and energy costs
- Relative cost of the stack is higher in Japan and Canada (in relative to U.S.) because of the higher labor costs.



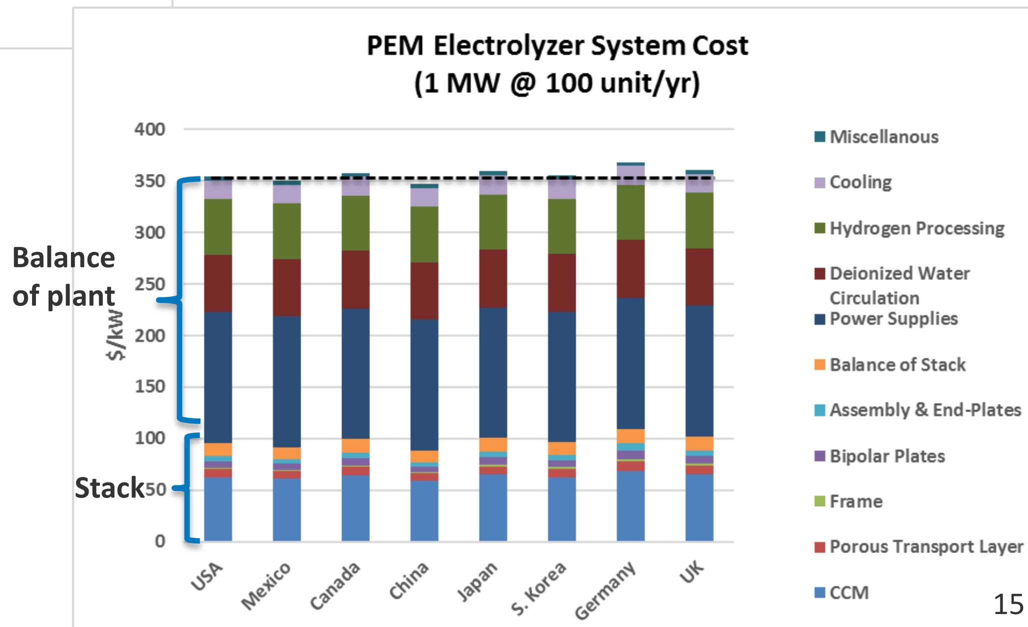
Accomplishment- PEM Electrolyzer System Cost



System cost by component (stack & BOS)

- Unlike the stack, balance of plant is not manufactured in house and most of its parts are outsourced from reliable vendors
- Balance of plant shares >50% of total system cost, and assumed to have same cost across all countries in the list

- Power electronics dominate the balance of plant cost (AC/DC rectifiers are very expensive compared to the DC/DC converter)
- Connecting electrolyzer to DC source (e.g., wind, PV) may reduce the cost of power electronics in the electrolysis system (e.g., AC-DC rectifier cost vs. DC-DC convertor cost)



Electrolysis Systems Value Chain

	Raw Materials	Membrane Electrode Assembly	Stack	+ Balance of System	Electrolyzer
Currently Shipped	Shipped globally	Shipped globally	Shipped regionally	Shipped globally	Shipped globally
Value Share* [Cumulative]	15% *[15%]*	7% *[22%]*	5% [27%]	73% [100%]	n/a [100%]
U.S. Strengths	n/a	• R&D Innovation • Manufacturing experience • Educated workforce	• Educated workforce • Synergistic industries and clustering (benefiting from fuel cell manufacturing)	• Availability of suppliers • Import and export policies (no tariffs)	• Availability of manufacturers • Support from federal and state programs (e.g., California and Northeast hydrogen infrastructure)
Areas Need Work	• Supply chain security for critical materials (e.g. platinum, Iridium, etc.)	• Cost of manufacturing • Automation/ advanced manufacturing (e.g., roll-to-roll) • Low-cost labor availability (compared to China and Mexico)	• Quality and performance of products • Cost of manufacturing • Automation of assembly process	• Standardization of parts • Cost of power electronics	• Lack of coordinated incentives and facilitation in some states

* Assuming 1 MW PEM electrolyzer system and 100 unit/yr production rate

Conclusions

- Alkaline water electrolyzers have lower current and power densities, but have lower system cost (per kW basis) because of lower electrode materials cost (no precious materials) and larger cell size
- PEM electrolyzers have higher power density which requires smaller stack areas in relative to alkaline stack. This could contribute to lower stack costs with economies of scale
- U.S. based manufacturers have advantages of low energy cost, availability of skilled workers, and intellectual property
- Emerging manufacturing technologies (e.g. roll-to-roll catalyst coating, plates nitriding/coating, full automated assembly line, etc.) in association with economies of scale will have great impact on the capital cost of onsite H_2 production systems and cost of H_2 generation

Remaining Challenges and Barriers

Our team is still working on several areas that could improve the impact of our analysis:

- Involve more organizations (industry, part suppliers, regulation agencies, etc.) in the hydrogen refueling station study
- Make new collaboration with industry in the ongoing project (manufacturing competitiveness analysis for onsite hydrogen production systems)
- Expand the cost study framework to cover CAPEX and OPEX and to compare cost of HRS to gas stations
- Benchmark our results with actual installations in several countries/regions
- There is a strong need to study manufacturing cost for balance of plant parts (e.g. AC-DC rectifier shares >20% of total PEM electrolysis system cost)

Proposed Future Work

- Complete manufacturing cost analysis onsite H_2 production systems
  - PEM electrolyzers
  - Alkaline electrolyzers

- Study effect of emerging manufacturing technologies and economies of scale on the onsite hydrogen production systems capital cost and impacts on hydrogen production cost

- Study effects of the change in capital cost on the cost of hydrogen production (CAPEX & OPEX)

- Benchmark our results with station installers and state/countries sponsoring new installations

"Any proposed future work is subject to change based on funding levels."

Responses to 2017 AMR Reviewer Comments

There was no discussion about the cost of a “gasoline refueling station,” which, although clearly less, is far from zero. It is interesting that gasoline is almost always dispensed from buried tanks, which are conveniently out of sight and have no footprint.

- Good point, this can be included in the total cost of ownership model in case we have time and resources to do so.

Hydrogen tanks tend to be inconveniently large and troublesome. The polymer electrolyte membrane (PEM) electrolyzer costs were interesting, especially the cost variation with volume. It would have been interesting to include costs of contemporary commercial electrolyzers at times that high-current devices have some predictive insight into the scaling issue.

- Cost models for PEM and alkaline electrolysis are being developed and refined this year. New PEM electrolyzers with high pressure and/or current capabilities will be studied if time allows.

It is not clear how margin is applied/varies with manufacturing rate. The basis of manufacturing rate cost reduction (“20% discount per 10x increase in purchased quantity”) is not explained.

- This assumption is based on some discussions we had with fuel cell and H_2 compressor manufacturers. It’s sort of rule-of thumb and may not get a wider acceptance in the fuel cell community. Also, we found something similar to this assumption when we collected the quotes from different vendors with different discount ranging between 5-35% in most cases.

Dispenser cost analysis has focused on H35 and dual H35/H70. It is not clear why the team did not focus on single-hose dispenser H70.

- H35 is still used for FC buses and trucks and H35/H70 is the current technology of dispensers which can fuel FCEV, FC-forklifts and FC-buses. H70 single hose dispenser will be added to the analysis.

There is not enough industry participation. This would be helpful in understanding what market conditions would bring more players into these new markets. OPEX is not taken into account with CAPEX. For example, the MCHE may be more expensive, but refrigeration power costs could be greatly reduced. It is unclear how the project team would address this. The project seems to be wandering in many directions and should be focused on HRS costs.

- That’s a really good point. While we are focusing on manufacturing cost in this work, we think that OPEX is also important to consider in the total cost of hydrogen stations. We did include this in the work for electrolysis systems

Collaborations

- David Hart, Franz Lehner, E4Tech, United Kingdom
  - Provided data for manufacturing cost analysis for PEM and alkaline electrolyzers
- Syed Saba, Forschungszentrum Jülich (FZJ), Germany
  - Provided cost data for PEM electrolyzer to validate our cost model
- Brian James, Strategic Analysis Inc.
  - Provided cost data for PEM electrolyzers
- Kevin Harrison, Bryan Pivovar, Guido Bender, Mark Ruth, Owen Smith, NREL
  - Provided critical inputs for cost model and discussed cost model results
- Industry stakeholders: provided estimates for dispenser cost (AEG and Magna Power (power supplies), Grundfos (water pumps), etc.)

Summary

- **Relevance**: to provide a framework for technoeconomic and supply chain analyses for hydrogen refueling stations and onsite hydrogen production systems
- **Approach**: Bottom-up cost analysis cost models and detailed supply chain maps.
- **Technical Accomplishments and Progress**:
  - Manufacturing cost models for onsite hydrogen production systems (alkaline and PEM)
  - Trade flow maps for global HRS's
- **Collaboration**: E4Tech, FZJ Institute
- **Proposed Next-Year Research**:
  - Complete manufacturing cost models for alkaline electrolyzer
  - Investigate effect of qualitative factors in the manufacturing competitiveness

Technology Transfer Activities

- Not applicable for this cost analysis

Thank You

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PR-6A20-71304

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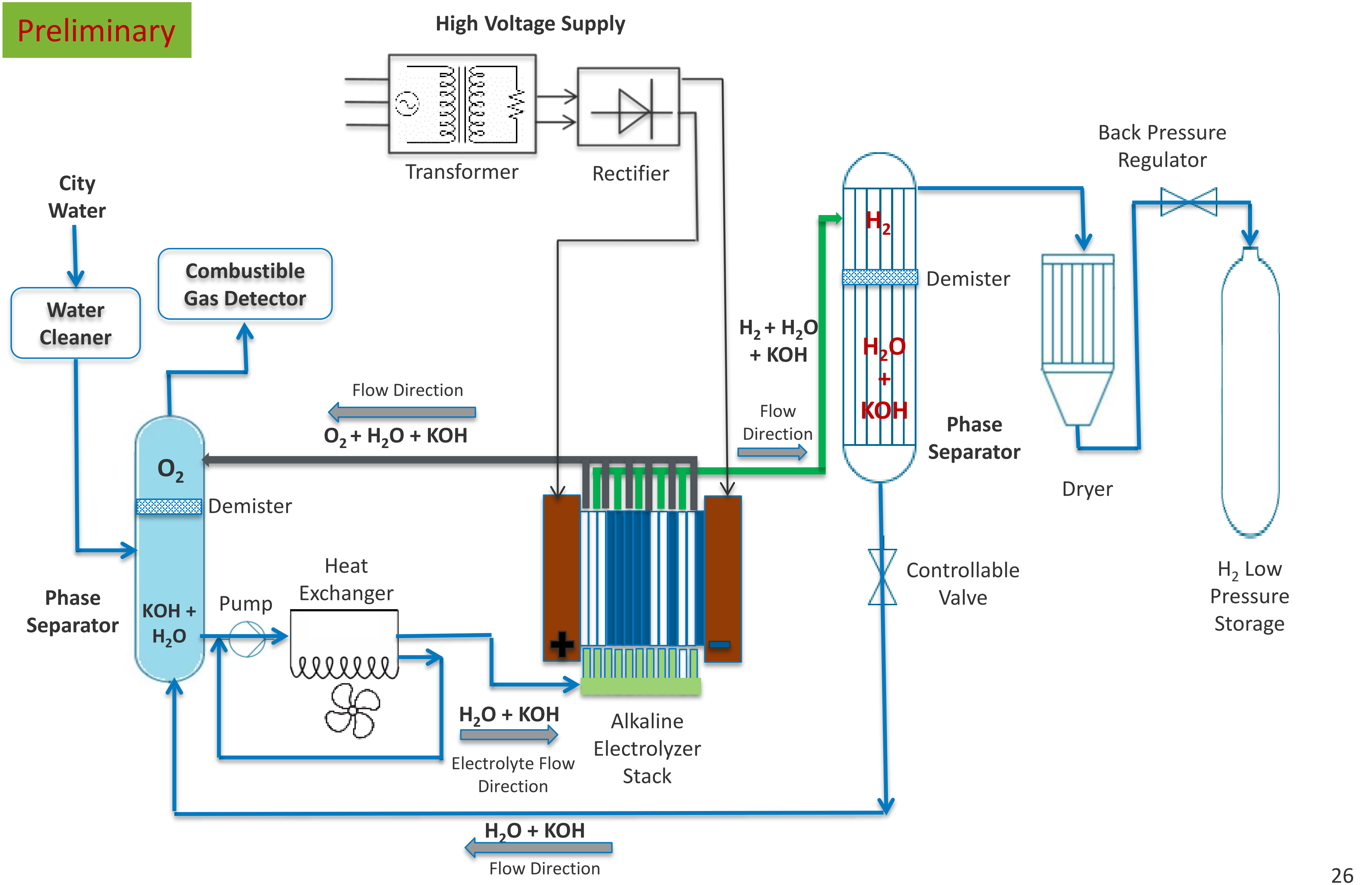
Technical Back-Up Slides

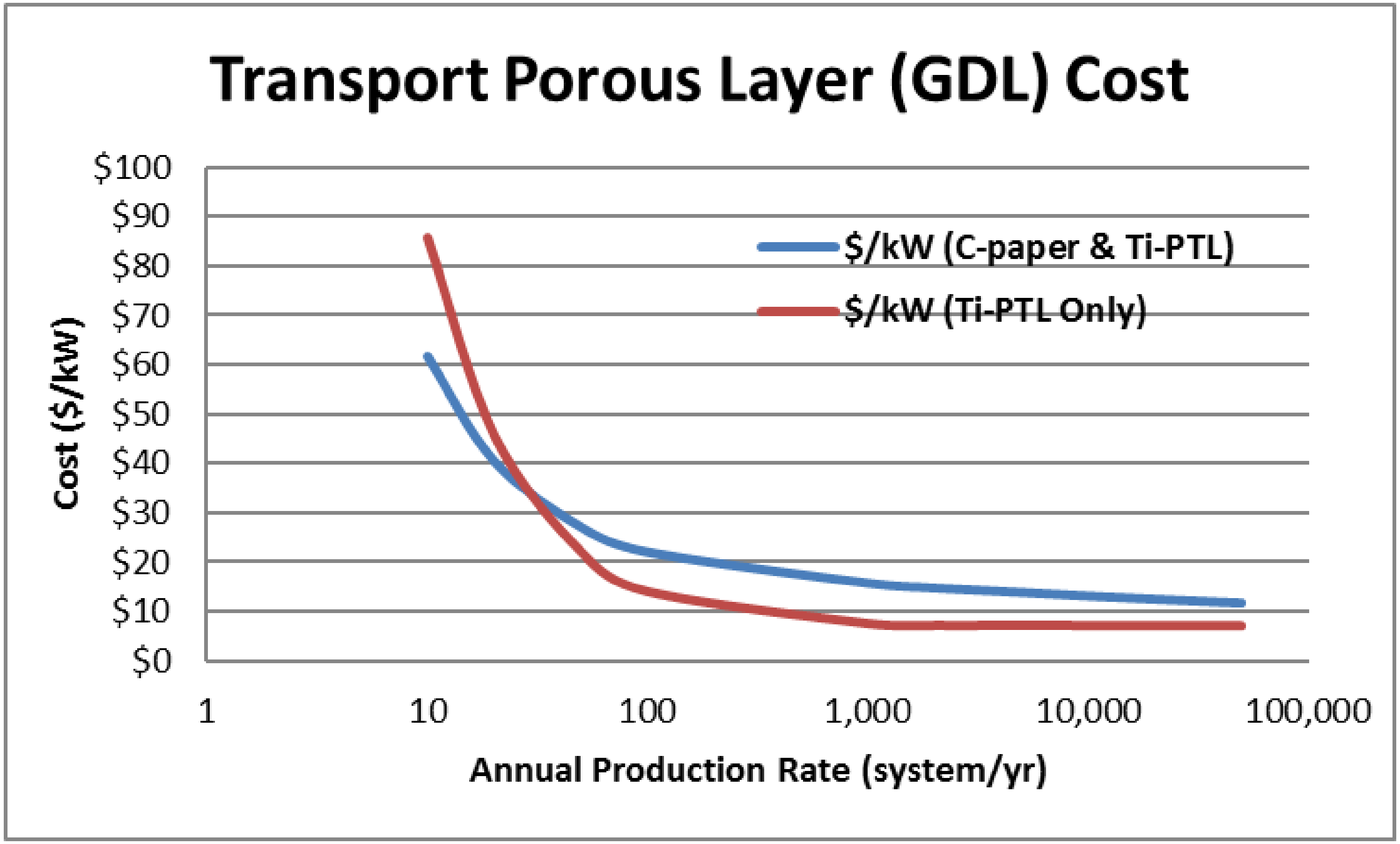
Alkaline Electrolyzer System

Preliminary



Porous Transport Layer Cost (PEM Electrolyzer)

Titanium layer performs better in the corrosive environment inside the stack. Could have lower cost at higher production rates

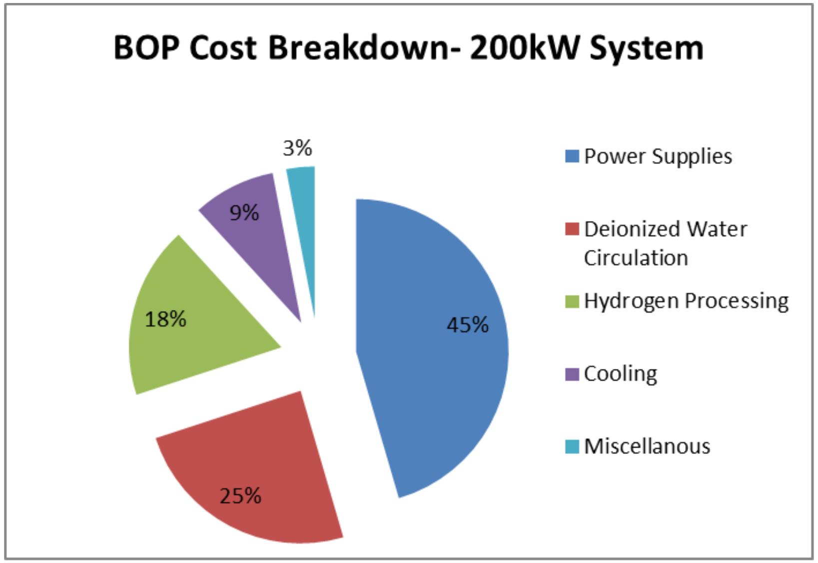


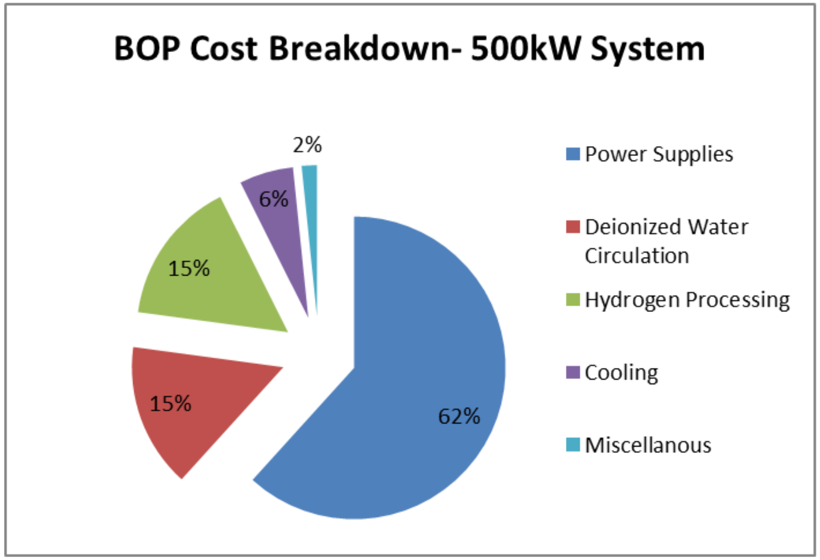
Cost curves for porous transport layers (also called GDL): 1) carbon paper on anode side and Ti-plate on cathode side, and 2) Titanium layer from both sides. Outsourced carbon layer, and Pt-PTL is manufactured in-house (30% porosity by volume).

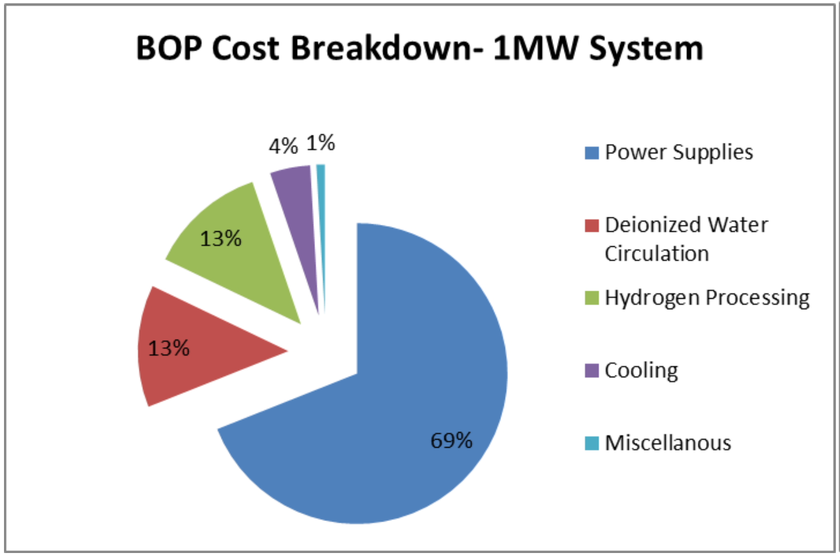
Annual production rate represents number of produced electrolyzers per year (200 kW system)

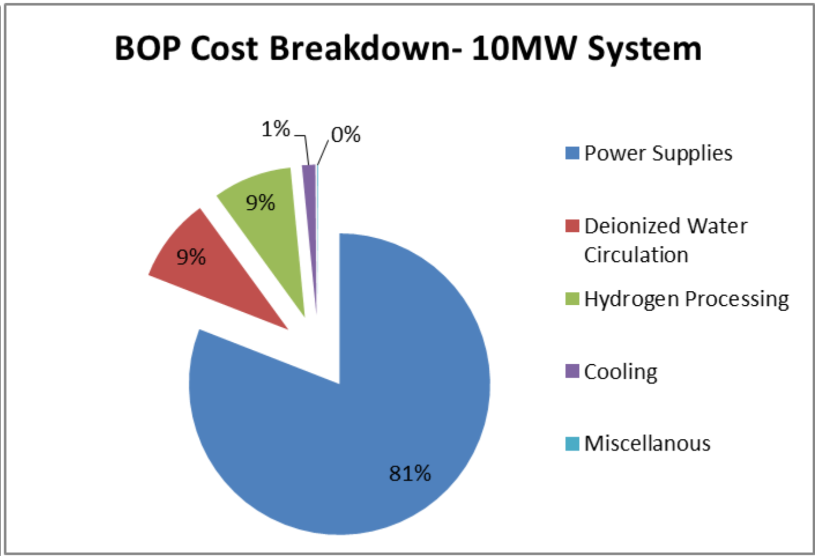
Balance of Plant Cost -PEM (Parts Only)

Parts only at low order quantities. Discounts are expected with larger quantities

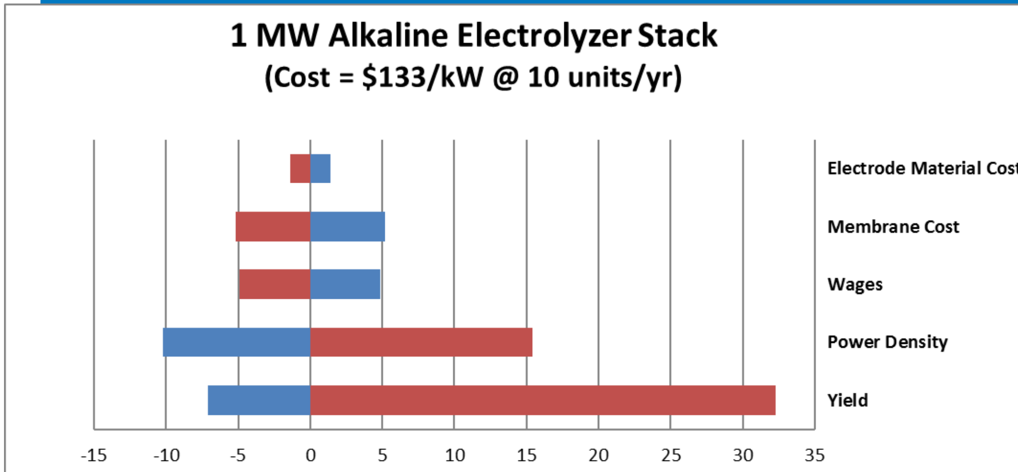








Sensitivity Analysis – Alkaline Electrolyzer Stack



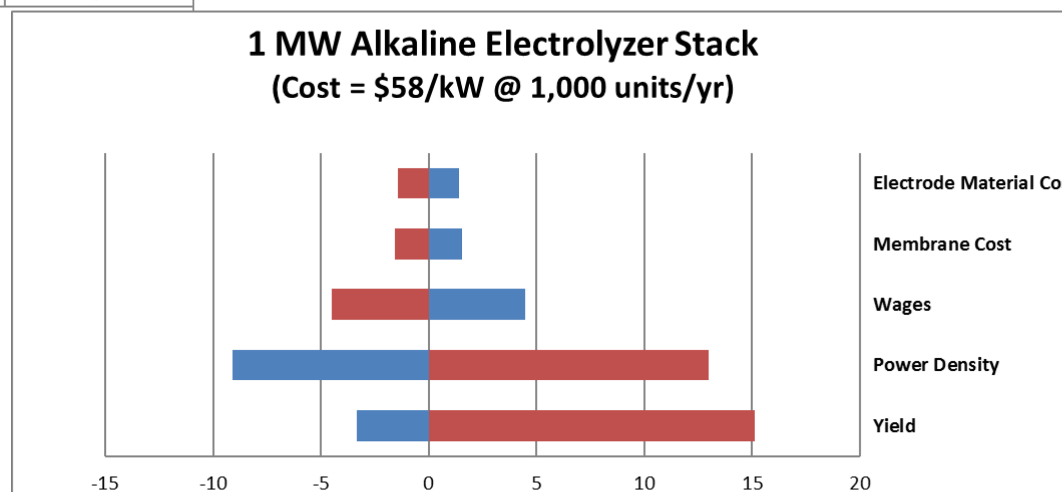
	Yield	Power Density	Wages	Membrane Cost	Electrode Material Cost
+20%	-$7	-$10	$5	$5	$1
-20%	$32	$15	-$5	-$5	-$1

Stack Only:

- Yield (scrap rate) (Base=95% for plates; 90% for membrane casting, 99.5% for stack assembly) dominates the stack cost at lower production rates

Stack Only:

- At higher production rates, power density and labor cost start to make larger impacts



	Yield	Power Density	Wages	Membrane Cost	Electrode Material Cost
+20%	-$3	-$9	$5	$2	$1
-20%	$15	$13	-$5	-$2	-$1