CEMAC
Clean Energy Manufacturing Analysis Center

Manufacturing Competitiveness Analysis for PEM and Alkaline Water Electrolysis Systems

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National Renewable Energy Laboratory

Fuel Cell Seminar and Energy Expo

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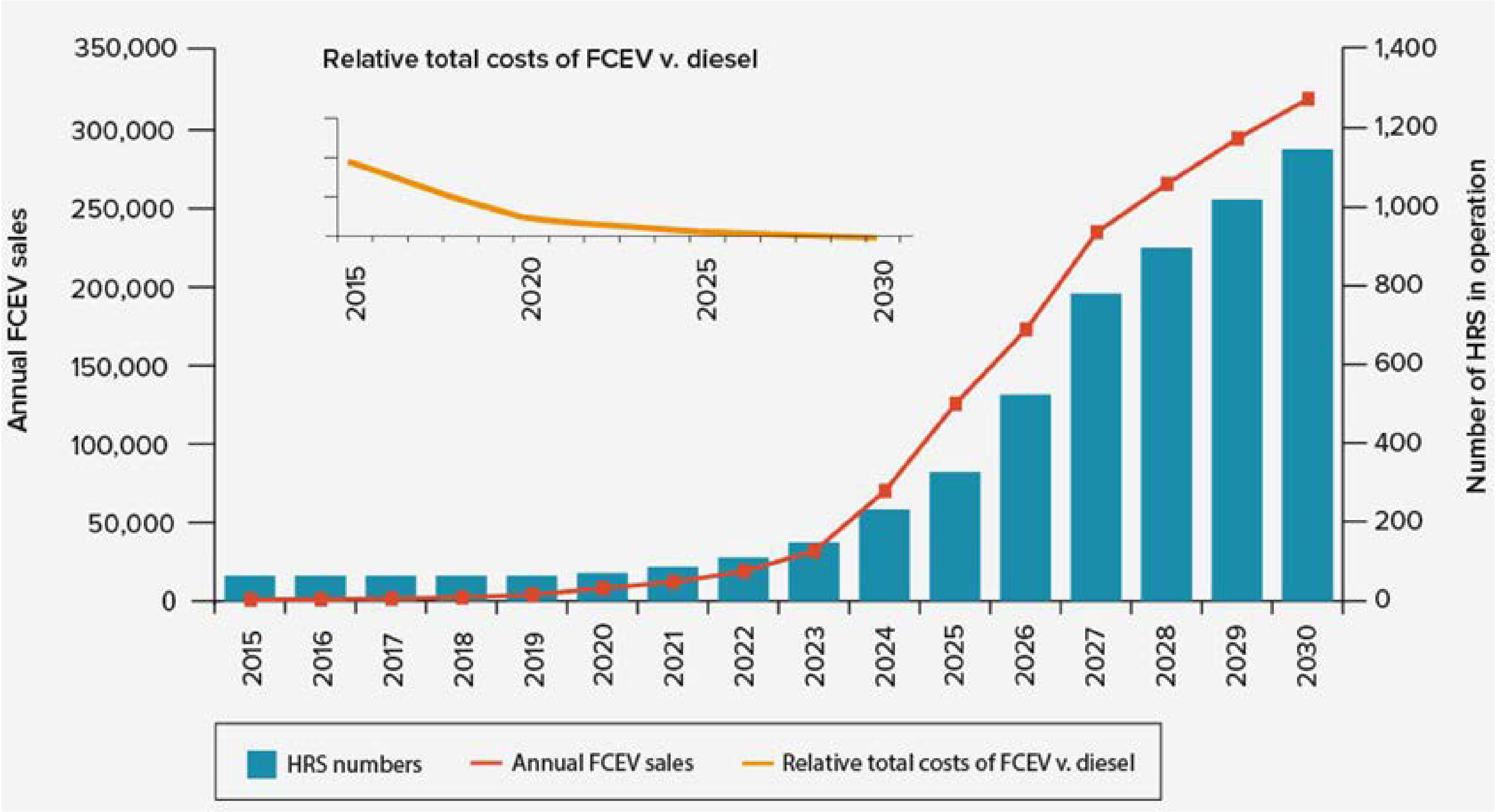
Agenda

- I. Introduction
- II. PEM Electrolyzer - Functional Specs & System Design
- III. Alkaline - Functional Specs & System Design
- IV. Cost Analysis for PEM and Alkaline Electrolyzer
- V. Concluding Remarks

I Introduction

Motivation: Infrastructure for Vehicles



- **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?**

Source: UkH2Mobility

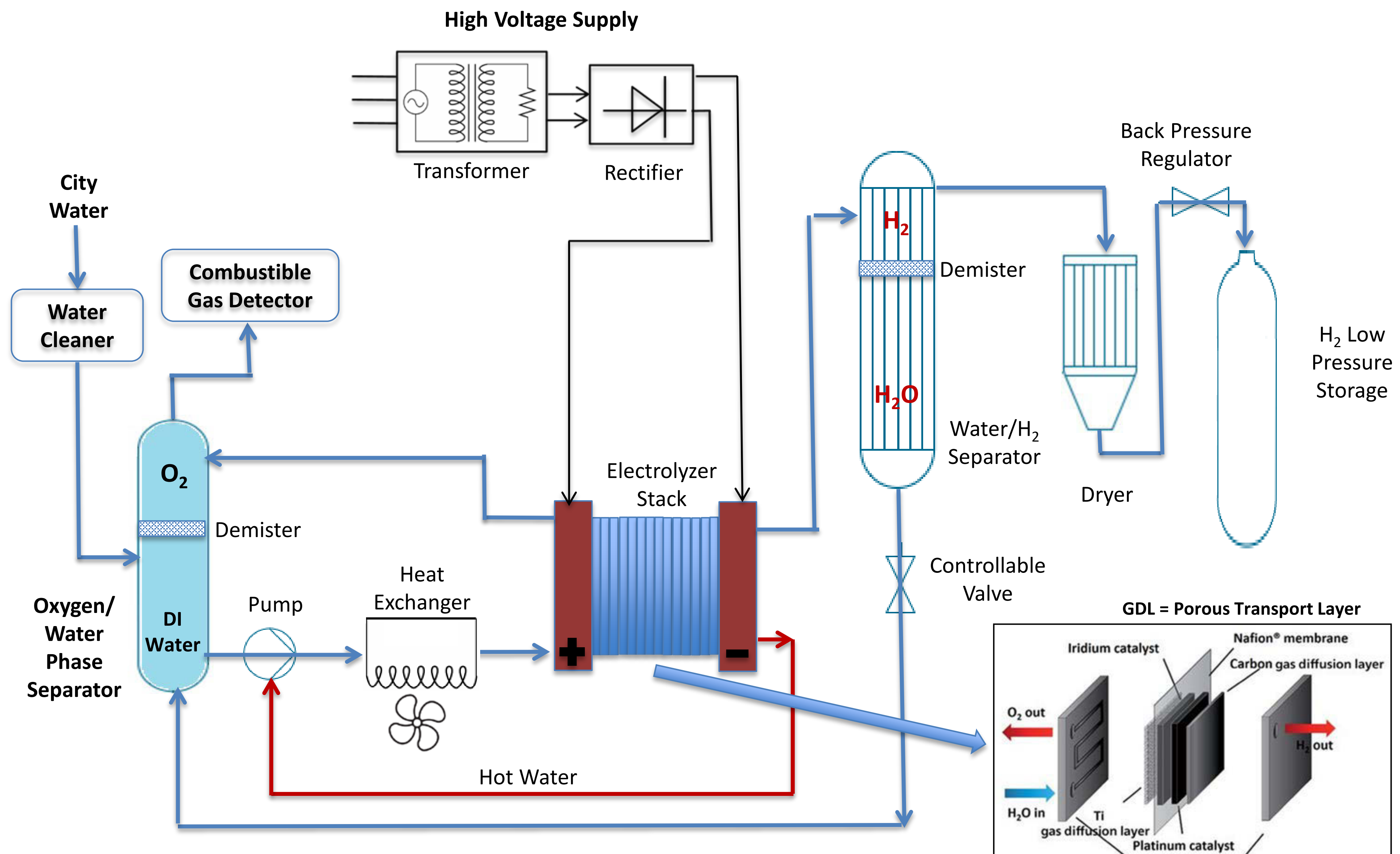
Comparison between PEM and Alkaline Electrolyzers

Characteristics	Alkaline	PEM	Unit	Notes
Current Density	0.2 - 0.7	1.0 - 2.2	A/cm^2	
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 2017

II PEM Electrolyzer - Functional Specs & System Design

PEM Electrolyzer System Design



* Stack components picture from greencarcongress.com

Derived Functional Specifications

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

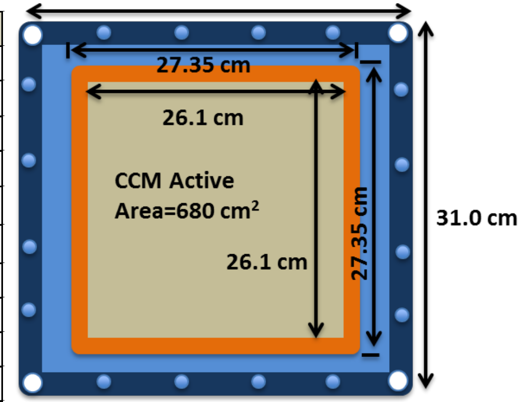
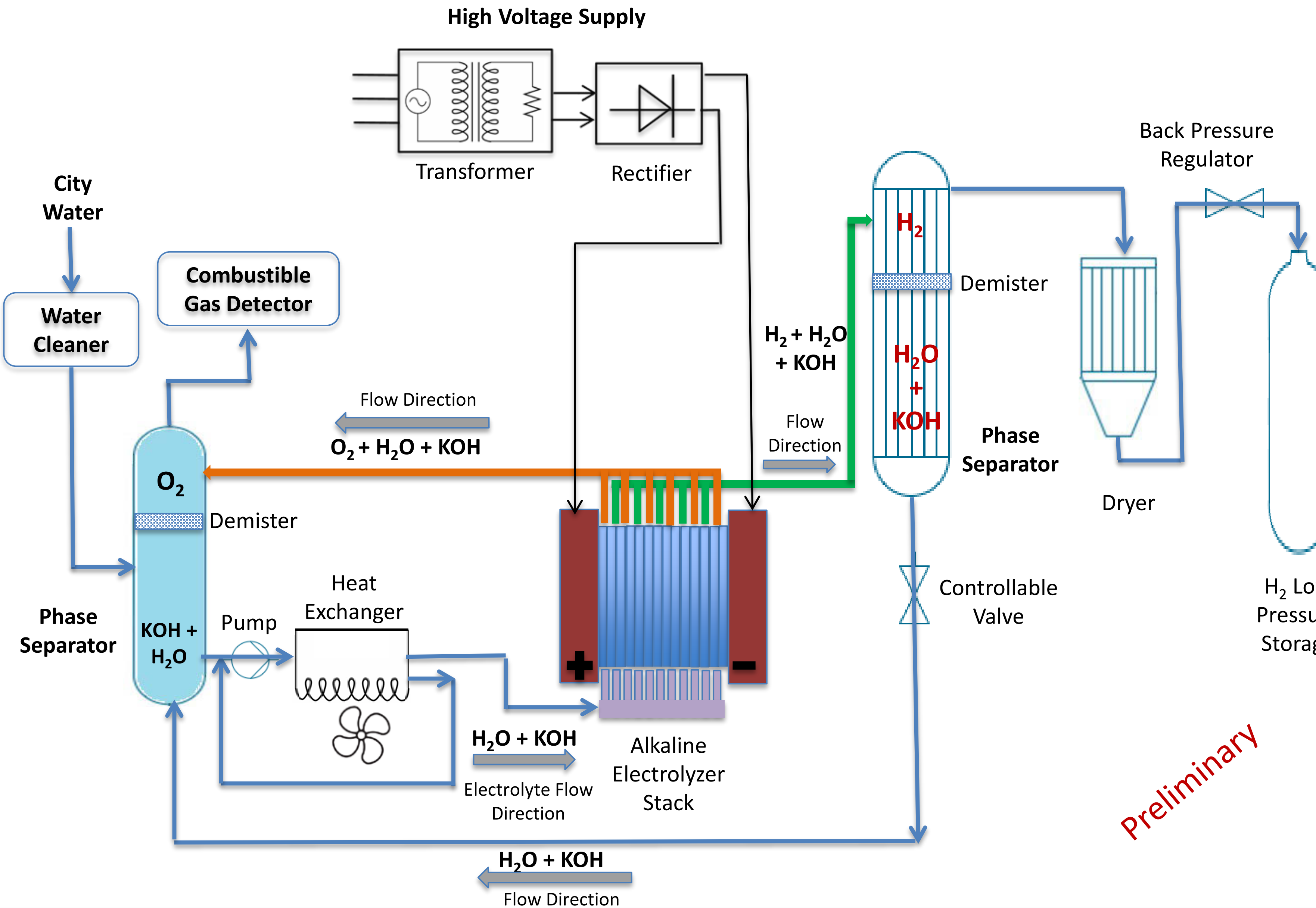


Plate area= 957 cm²

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	Stainless steel 316L	Coated (plasma Nitriding)

III Alkaline Electrolyzer - Functional Specs & System Design

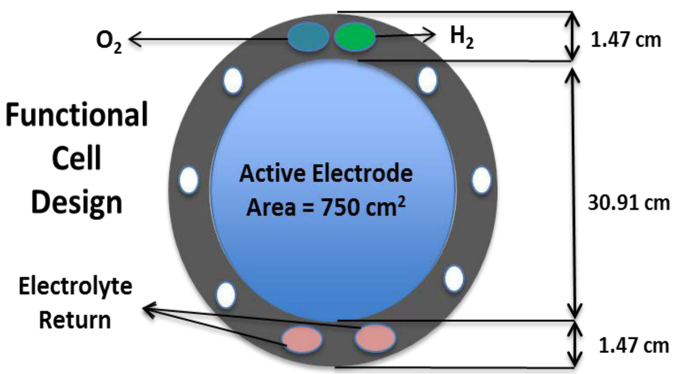
Alkaline Electrolyzer System



Alkaline Electrolyzer - Functional Specs

System rated power	10	20	50	100	200	500	1,000	2,000	5,000	10,000	kW
Electrolyte	H_2O+ 30% KOH						H_2O+ 30% KOH				
Single cell amps	150	150	150	150	150	150	300	300	300	300	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	V
Power density	0.336	0.336	0.336	0.336	0.336			0.336	0.336	0.336	W/cm^2
Single cell power	252.0	252.0	252.0	252.0	252.0	252.0	504.0	504.0	504.0	504.0	W
Cells per system	40	80	199	397	794	1,985	1,985	3,969	9,921	19,842	cells
Stacks per system	1	1	2	2	4	10	10	20	50	100	stacks
cells per stack	40	80	100	199	199	199	199	199	199	199	cells

Area Doubled



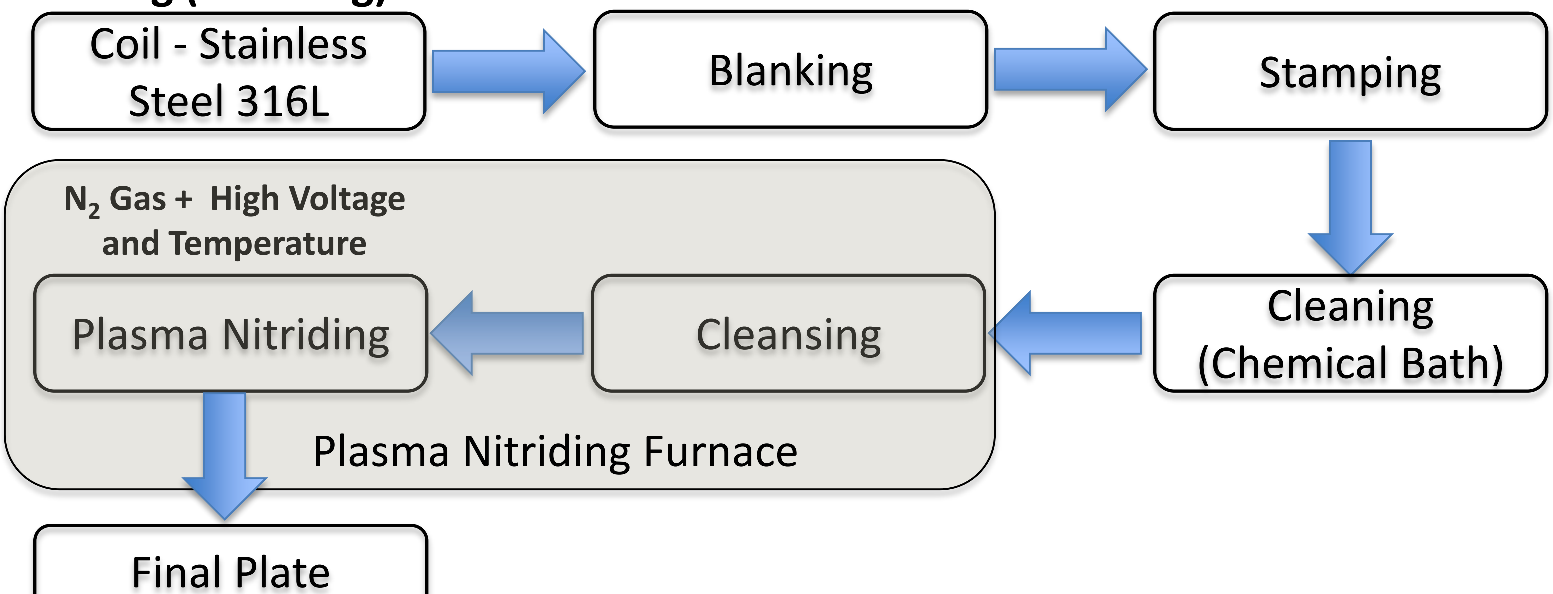
Part	Materials	Notes
Membrane	m-PBI	Cast membrane using doctor-blade machine
Electrodes	Raney-nickel	PVD + Leaching to get the required porosity
Porous Transport Layer	Pure Nickel Sheets	Corrosion resistance in alkaline solution
Frame	PPS-40GF or PEEK	Injection molding
Plates	Nickel plates	Surface treatment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

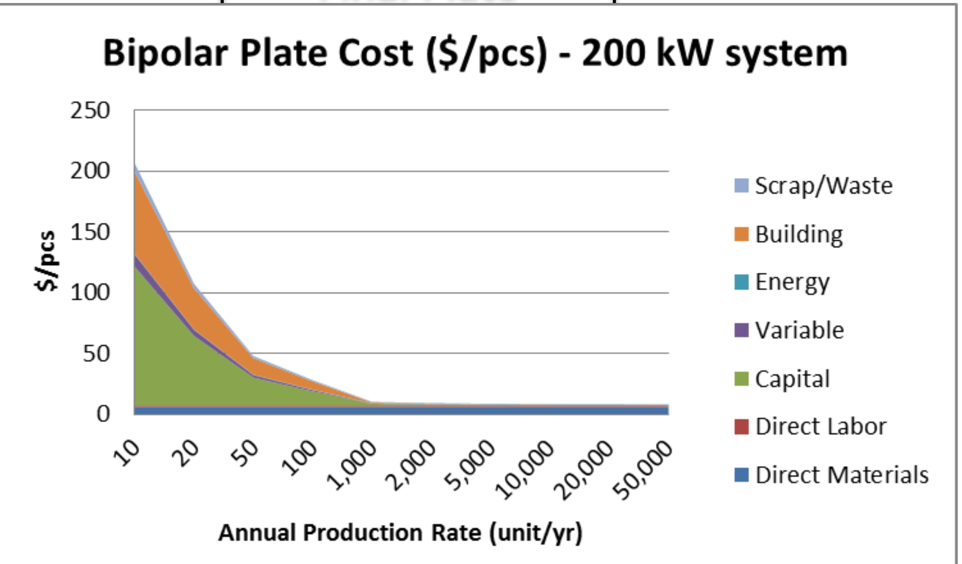
PVD: physical vapor deposition

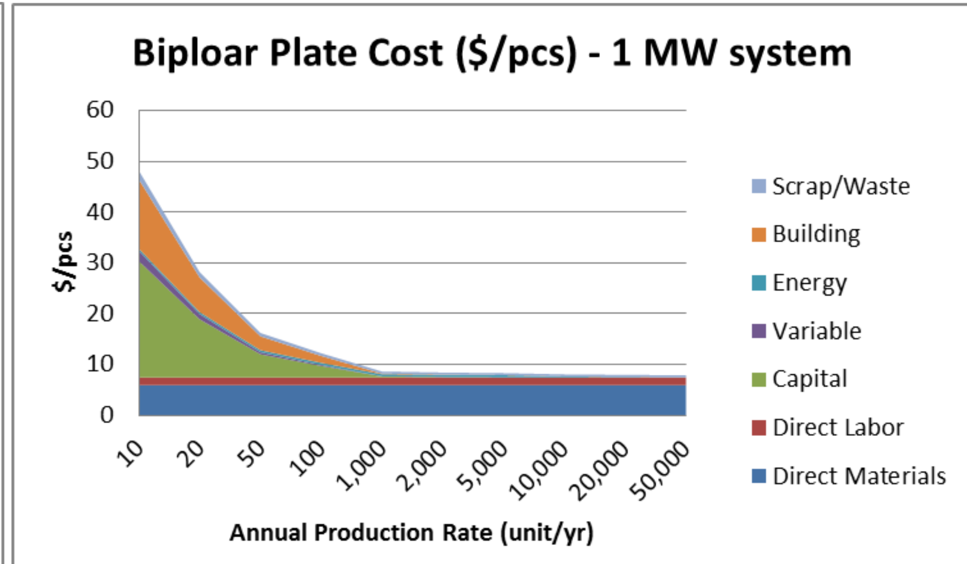
IV Cost Analysis for PEM and Alkaline Electrolyzer

PEM - Bipolar Plate

Case Hardening (Nitriding)







PEM Stack Assembly

- 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)

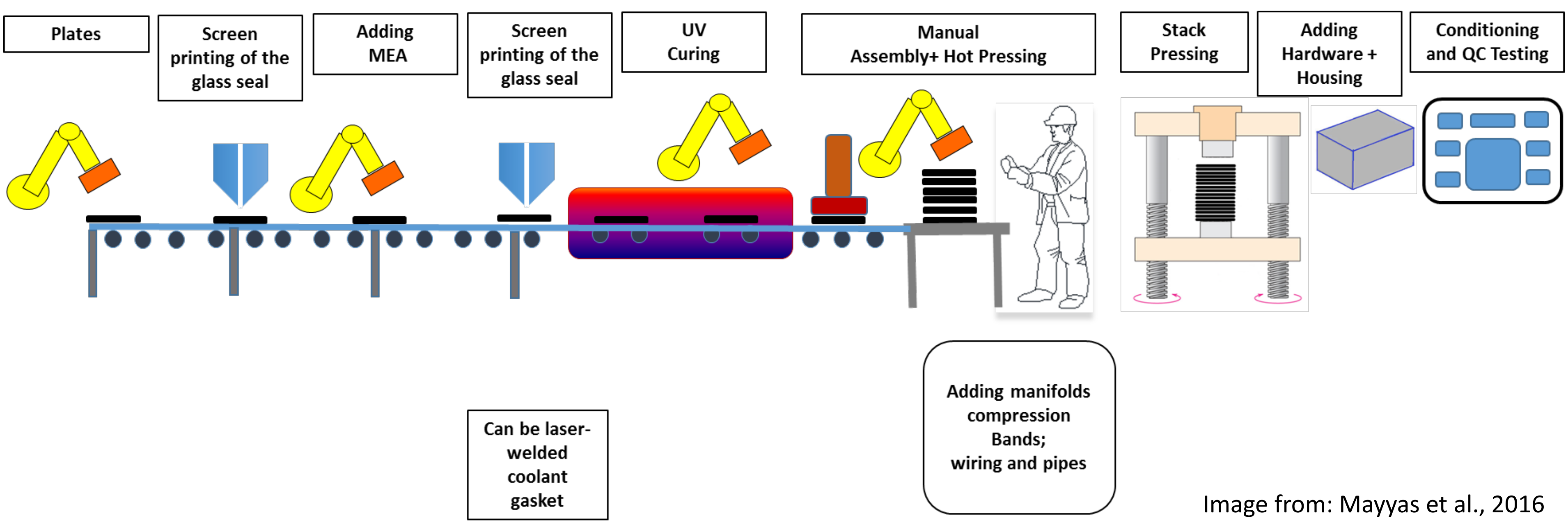
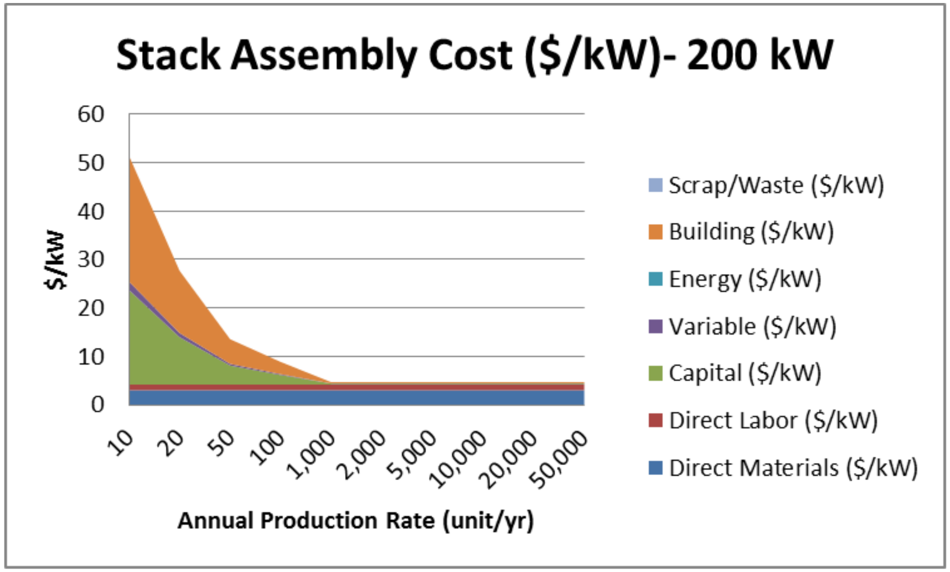
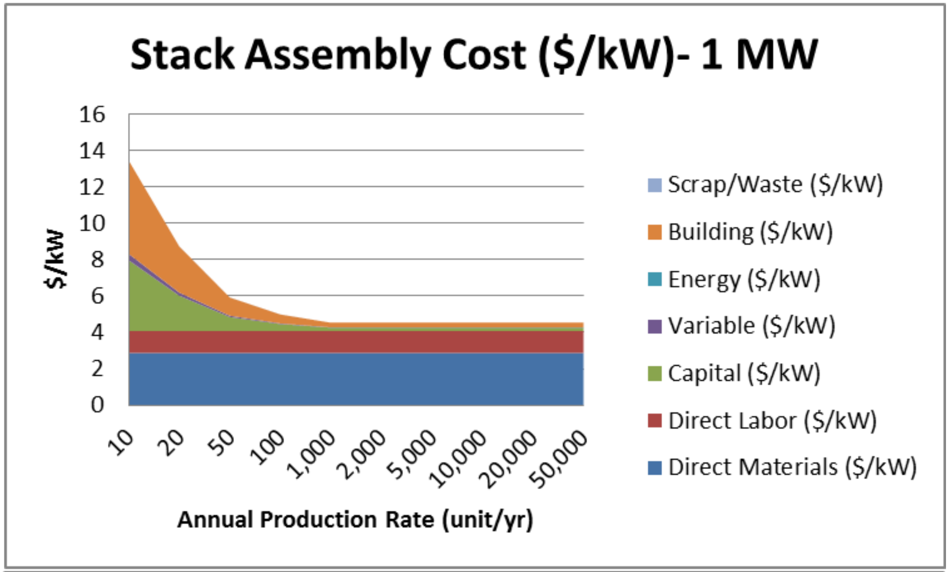
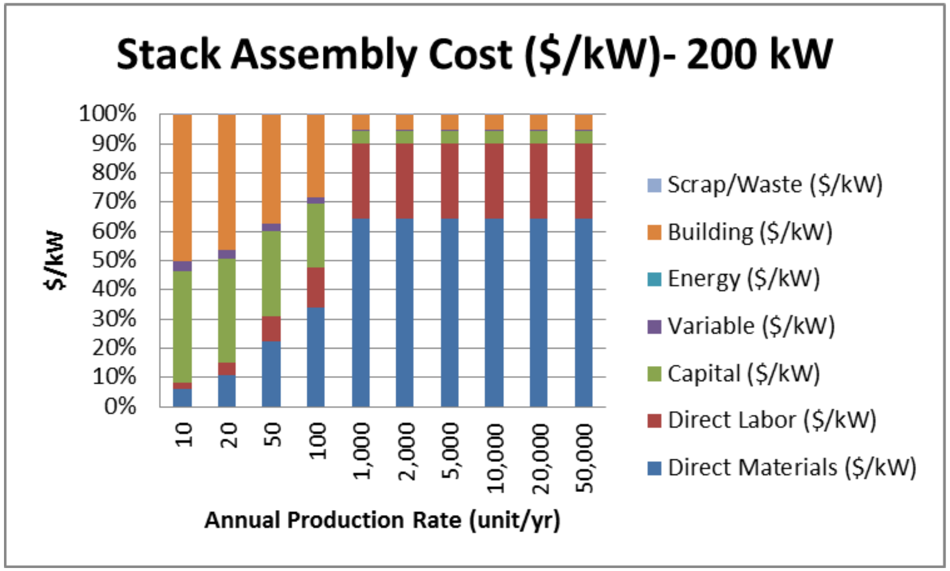


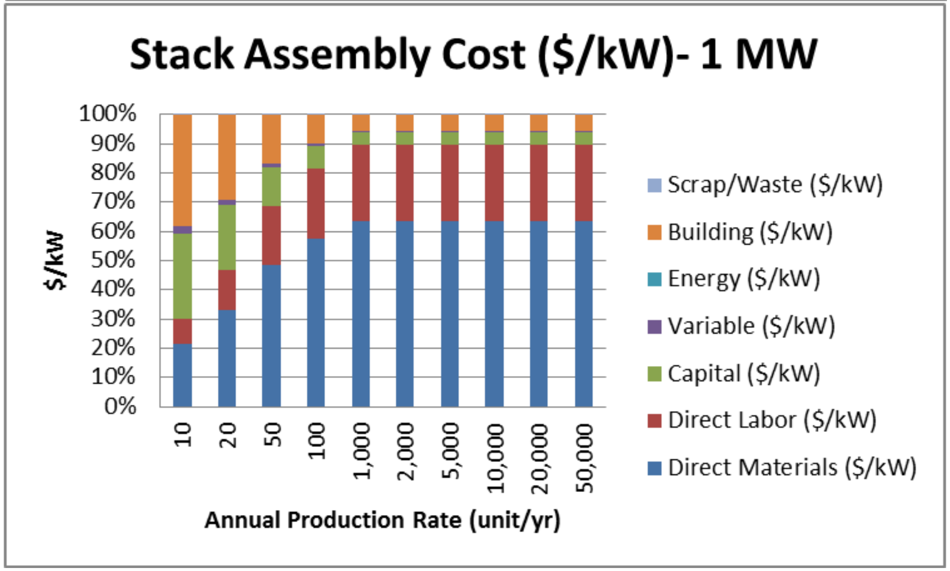
Image from: Mayyas et al., 2016

PEM – Stack Assembly







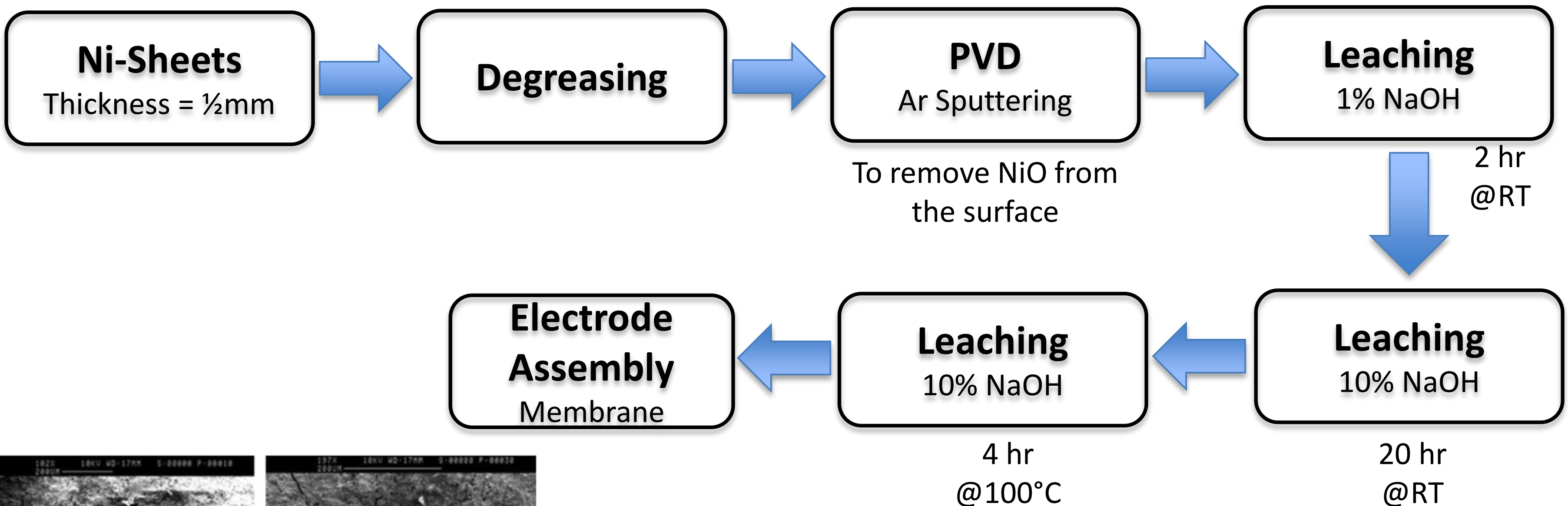


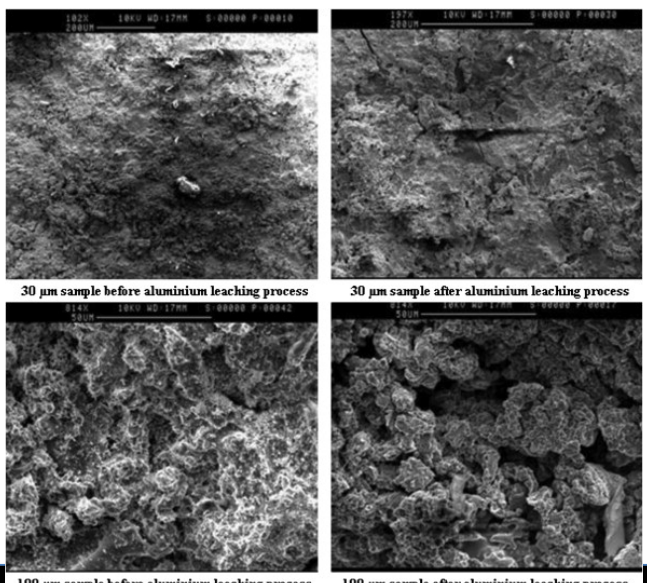
65 kg H_2/day

385 kg H_2/day

Alkaline - Raney Nickel Electrodes

Process Flow Diagram





30 μm sample before aluminium leaching process

30 μm sample after aluminium leaching process

100 μm sample before aluminium leaching process

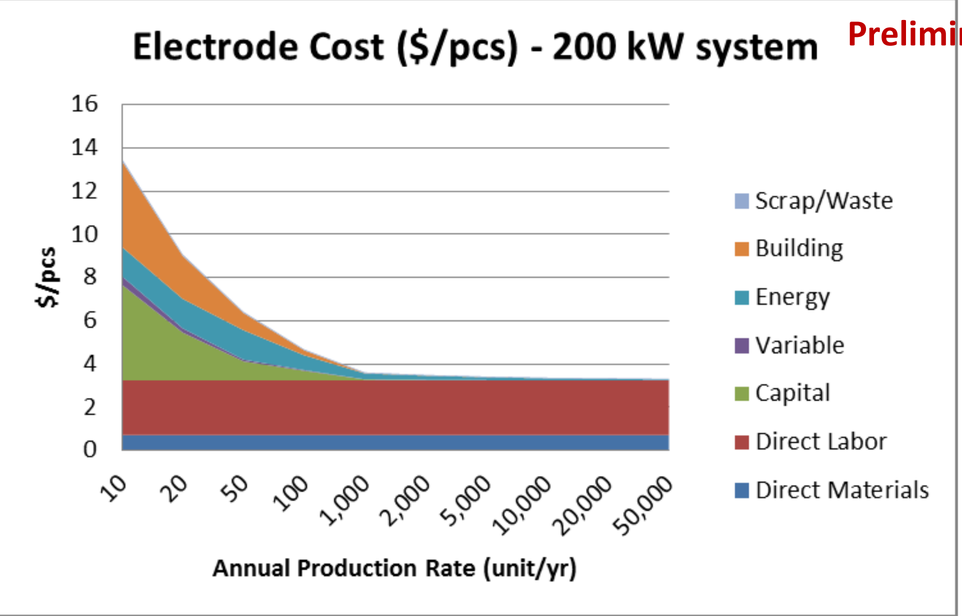
100 μm sample after aluminium leaching process

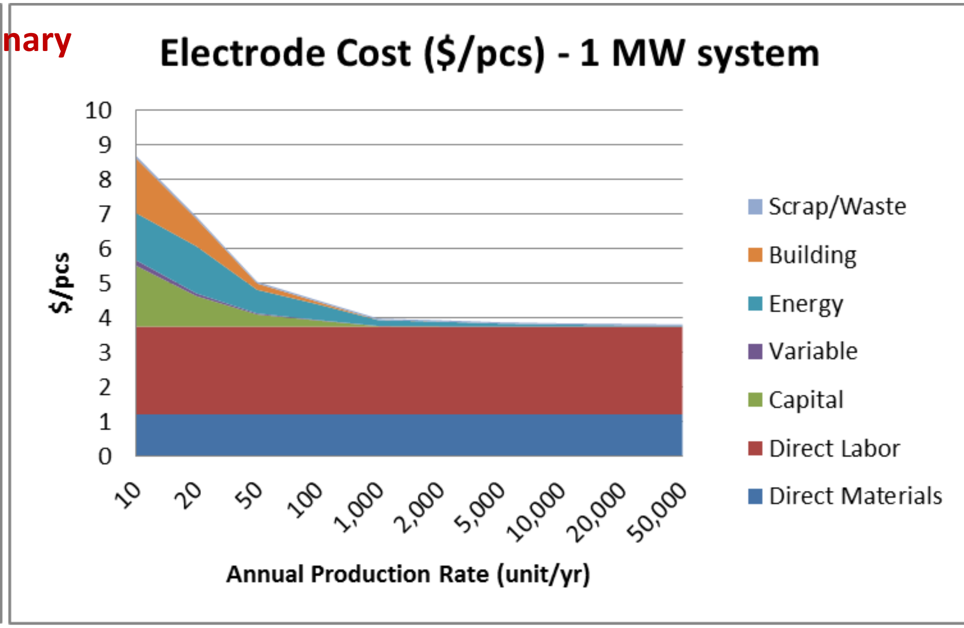
Leaching can be made in one step with longer time and higher concentration of NaOH (~30%)

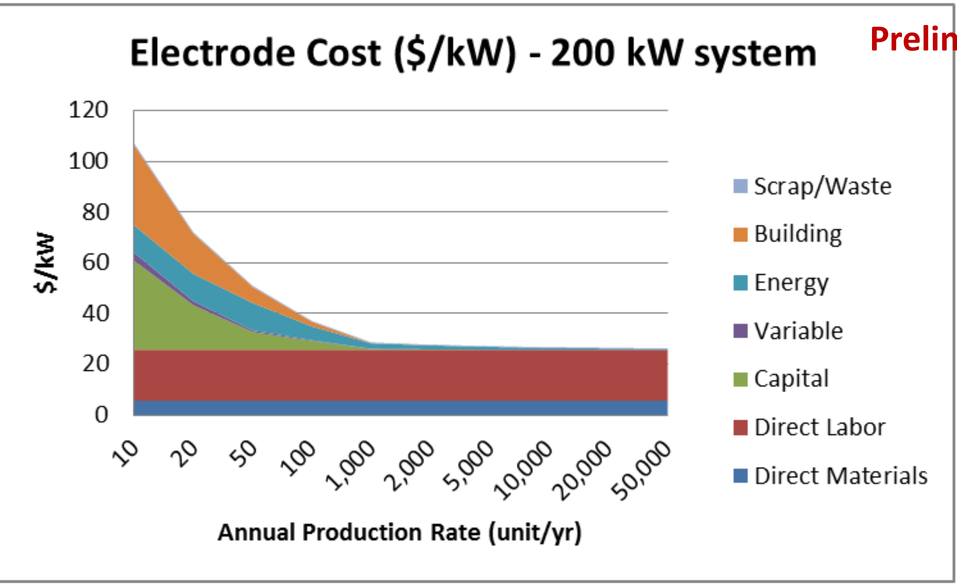
Image from Chade et al., 2013

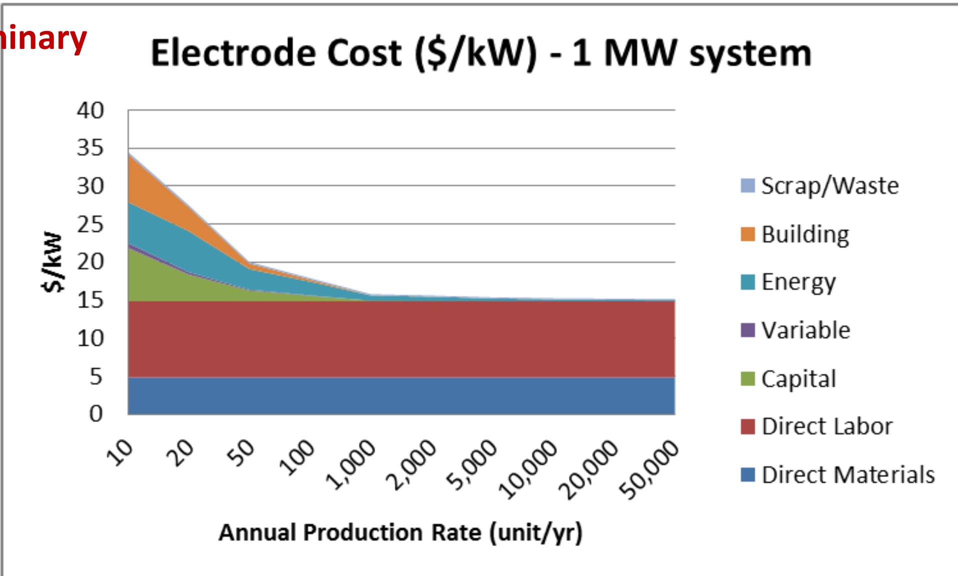
Based on Kjartansdo´ttir et al., 2013

Alkaline - Raney Nickel Electrodes

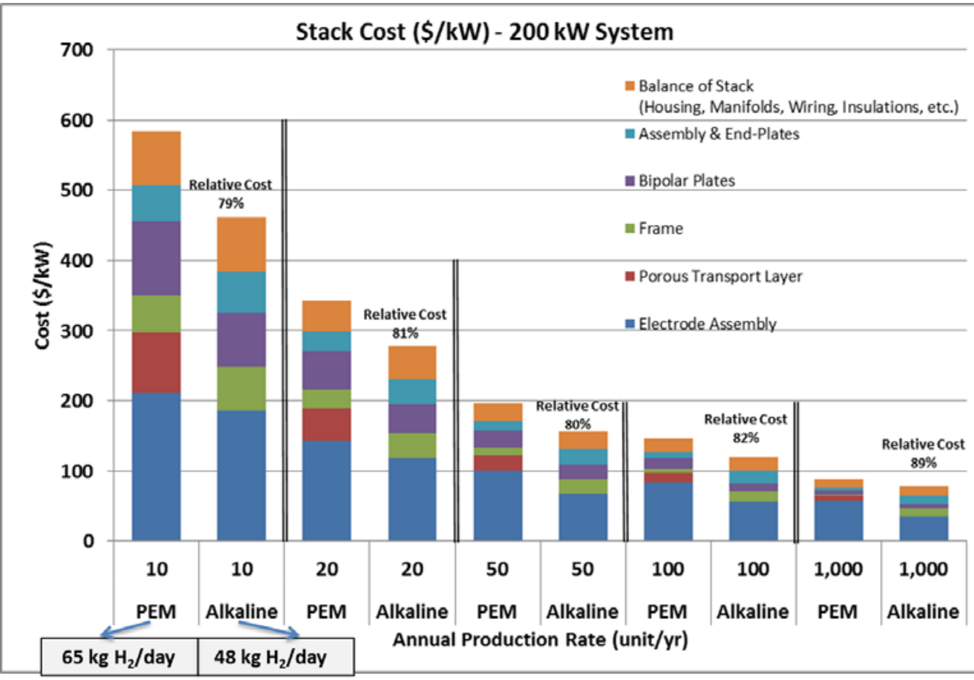






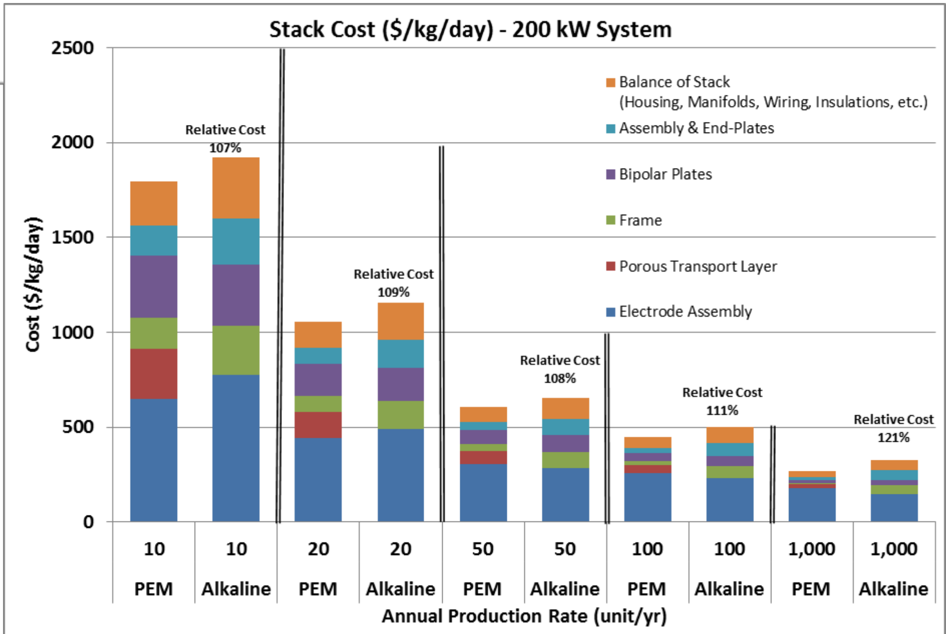


Manufacturing Cost of Electrolyzer Stacks

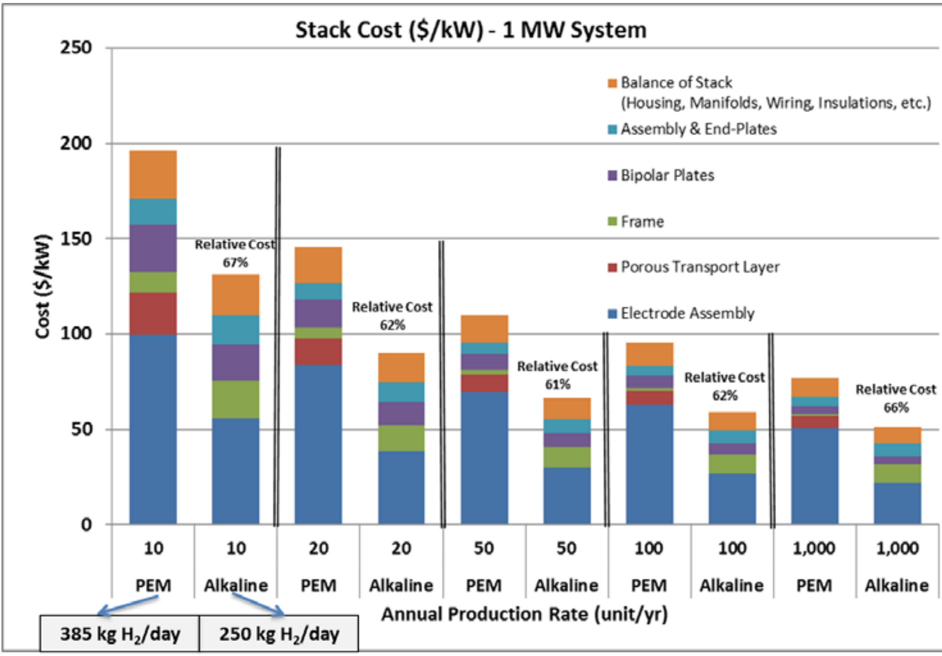


- Alkaline electrolyzer stacks have larger cost in $/kg-$H_2$
- *Cost curve for a 200kW system*

A comparative cost analysis between PEM and alkaline stacks using hydrogen production rates (not the cost of making hydrogen from the electrolyzers)

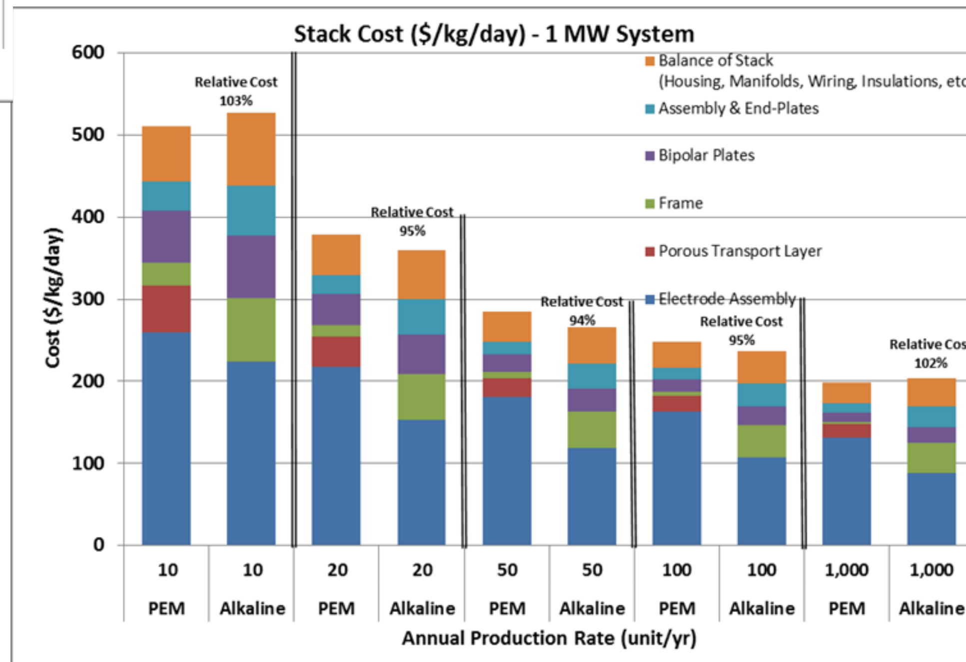


Manufacturing Cost of Electrolyzer Stacks



- Alkaline electrolyzer stacks have larger cost in $/kg-H_2$ basis
- *Cost curve for a 1MW system*

A comparative cost analysis between PEM and alkaline stacks using hydrogen production rates (not the cost of making hydrogen from the electrolyzers)



V Concluding Remarks

Conclusions

- Alkaline water electrolyzers have lower current and power densities, but have lower initial cost (per kW basis)
- PEM electrolyzers *may* have lower stack cost in ($ per Nm^3/hr)
- Good similarities in manufacturing processes for PEM and alkaline electrolysis (e.g., membrane casting, plates stamping & coating, end plates, stack assembly, etc.)

Questions?

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THANK YOU!

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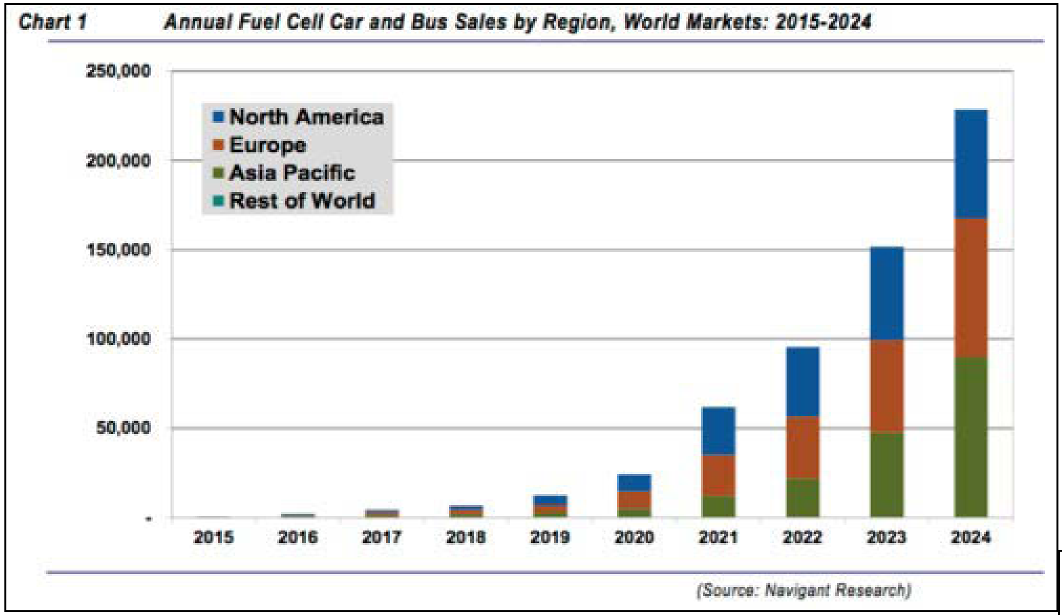
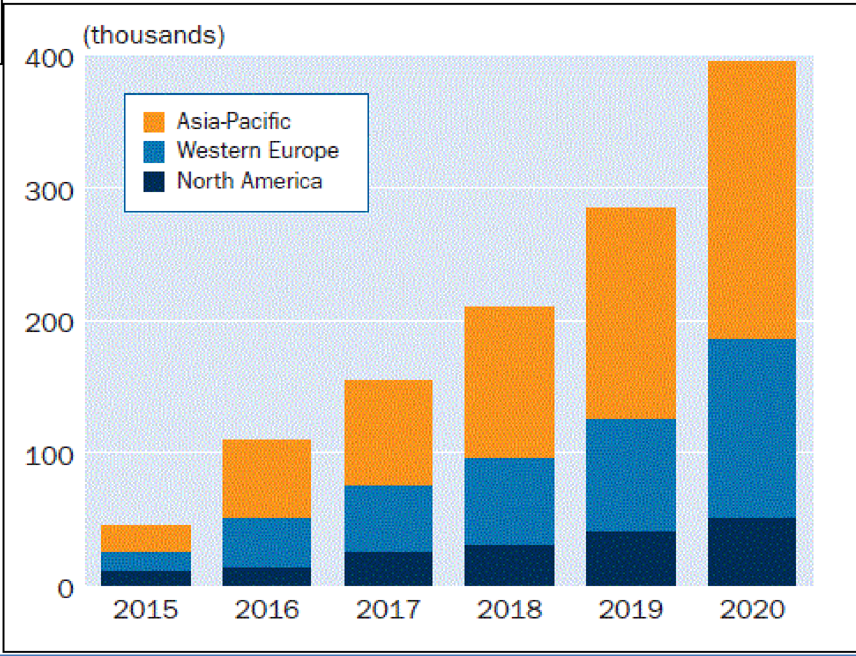
Backup Slides

FCEV 2015-2024





International Manufacturer of Onsite Hydrogen Production System

Alkaline Electrolyzer **PEM Electrolyzer** **Reformers**

This map can be accessed from https://maphub.net/mayyas111/Onsite-H2-Production-Equipment

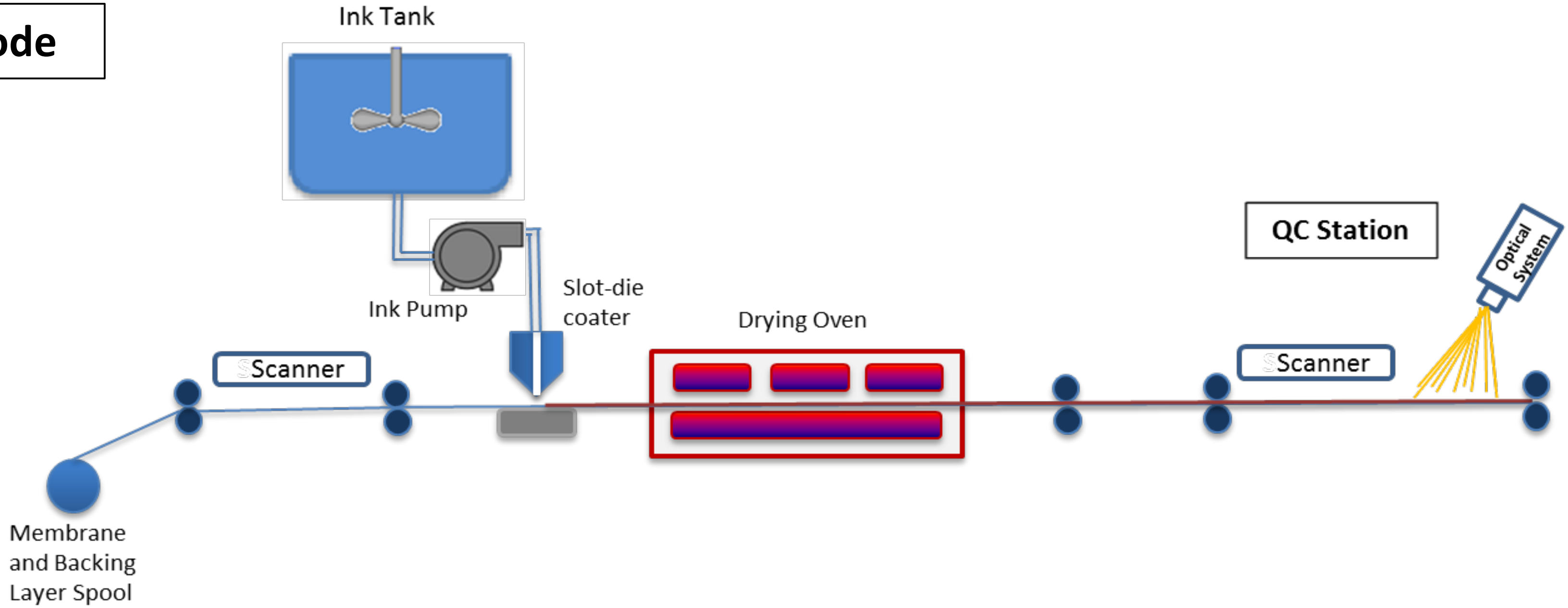
PEM Electrolysis

PEM - Functional Specifications

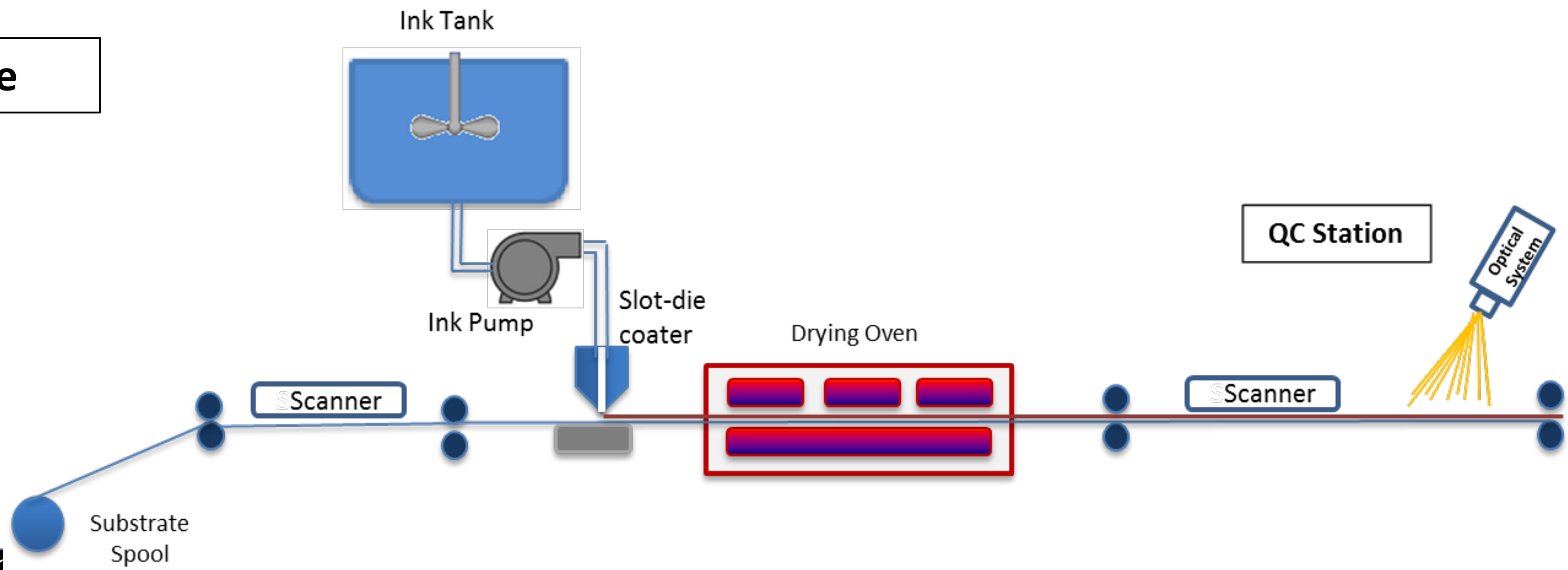
	Manufacturer	Hydrogenics	Hydrogenics	Proton OnSite	Proton OnSite	Proton OnSite	Proton OnSite	Giner	Proton OnSite	Siemens	Units
	Model Number	HyLYZER™-1	HyLYZER™-2	H2	H2	H6	FuelGen12, Series	Merrimack		SILYZER 200 basic	
System	Electrolysis type	PEM (Proton Exchange Membrane)	PEM (Proton Exchange Membrane)	PEM (Proton Exchange Membrane)	PEM (Proton Exchange Membrane)	PEM (Proton Exchange Membrane)	PEM (Proton Exchange Membrane)	PEM (Proton Exchange Membrane)	PEM (Proton Exchange Membrane)	PEM (Proton Exchange Membrane)	
	Rated stack Consumption	7.20	14.40	14.00	28.00	40.00	45.00	160.00	250.00	1250.00	kW
	Startup time:							millisecond scale		< 10 sec	Sec
	Hydrogen purity (dep. on operating point):			99.9995%	99.9995%	99.9995%	99.9995%		99.3-99.8%	99.5% – 99.9%	
	System Effciency	6.70	6.70	7.30	7.00	6.80	7.50		6.25	5.56	kWh/Nm^3
	Net Prodution Rate	1	2	2	4	6	6	30.59	40	225	Nm^3/h
	Net Prodution Rate (scfh)	38	76	76	152	228	228	1162	152	8,550	scfh
	Net Prodution Rate (kg/day)	2.16	4.32	4.31	8.63	12.94	12.95	66.00	86.30	485.46	kg/day
	kW per kg/day ratio	3.34	3.34	3.25	3.24	3.09	3.48	2.42	2.90	2.57	kW per kg/day
	Turndown Ratio	0 to 100%		0 to 100% net product delivery (Automatic)	0 to 100% net product delivery (Automatic)	0 to 100% net product delivery (Automatic)		10:1	10-100%		%
	Output pressure	Up to 7.9	Up to 7.9				15	0-40 bar	up to 12 bar	Up to 35	bar
	Feed Water						Potable main water supply		Deionized water		
	Fresh water demand:	1	1	1.83	3.66	5.5	54		3.4 ltr/hr	1.5	ltr / Nm³ H2
	Inlet water pressure	0.7-6.9	0.7-6.9	1.5 to 4	1.5 to 4	1.5 to 4	1 to 10				barg
	Relative Humidity	0 to 90%		0 to 90%	0 to 90%	0 to 90%					%
	Power Supply	208/120,3 phase,4 wire+gnd,50/60 Hz 200-260,1 phase,2 wire+gnd, 50/60 Hz Direct connection to DC possible upon request.		380 to 480 VAC, 3 phase, 50 or 60 Hz	380 to 480 VAC, 3 phase, 50 or 60 Hz	380 to 480 VAC, 3 phase, 50 or 60 Hz	420-480 VAC, 3 phase, 60 Hz, 112 FLA		400VAC 50Hz		
	Cooling strategy	Air Cooled	Air Cooled	Liquid cooled 8.1 kW	Liquid cooled 16.1 kW	Liquid cooled 23.7 kW			Air or Liquid	Air Cooled	
	Operating Temperature	5 to 40	5 to 40	5 to 60	5 to 60	5 to 60	-23 to 46		5 to 35		°C
	Hydrogen quality 5.0:									Optional DeOxo dryer	
	Hydrogen production under nominal load:										
	Life cycle design:									> 80,000 h	
	CE Approved							CE Mark with PED and ASME	Yes	Yes	
Other Specs	Other Specs							Circular cells with 300 cm^2			
	Dimensions	0.75 X 0.66 X 1.17	1.30 X 1.00 X 1.25	180 cm x 81 cm x 191 cm	180 cm x 81 cm x 191 cm	180 cm x 81 cm x 191 cm	2.18 X0.84 X1.91		0.85 X 1.05 X 1.65	6.3 X 3.10 X 3.00	mXmXm
	Weight	250	275	682	858	908	900		260	17000	kg

CCM Slot-Die Coating Process

Cathode

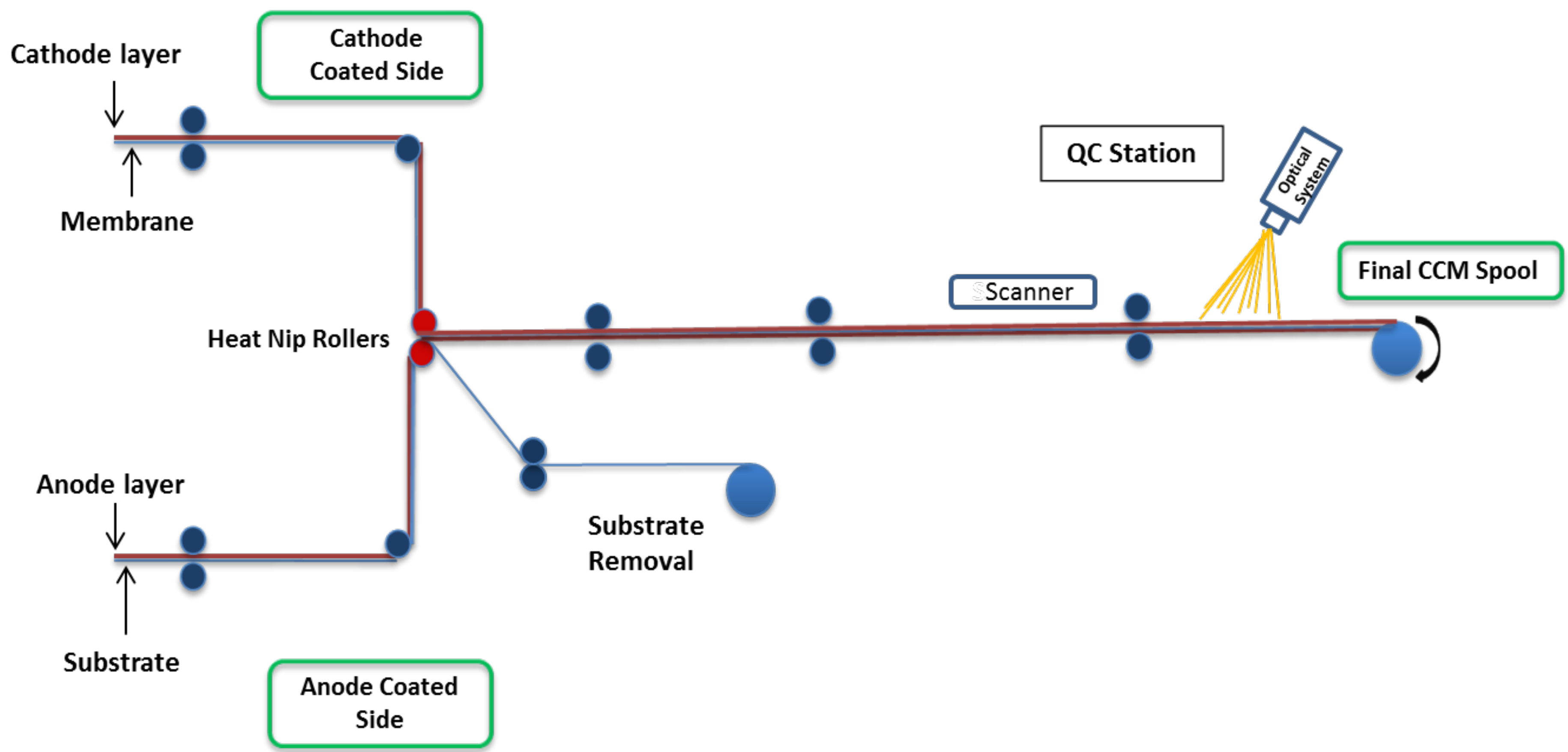


Anode

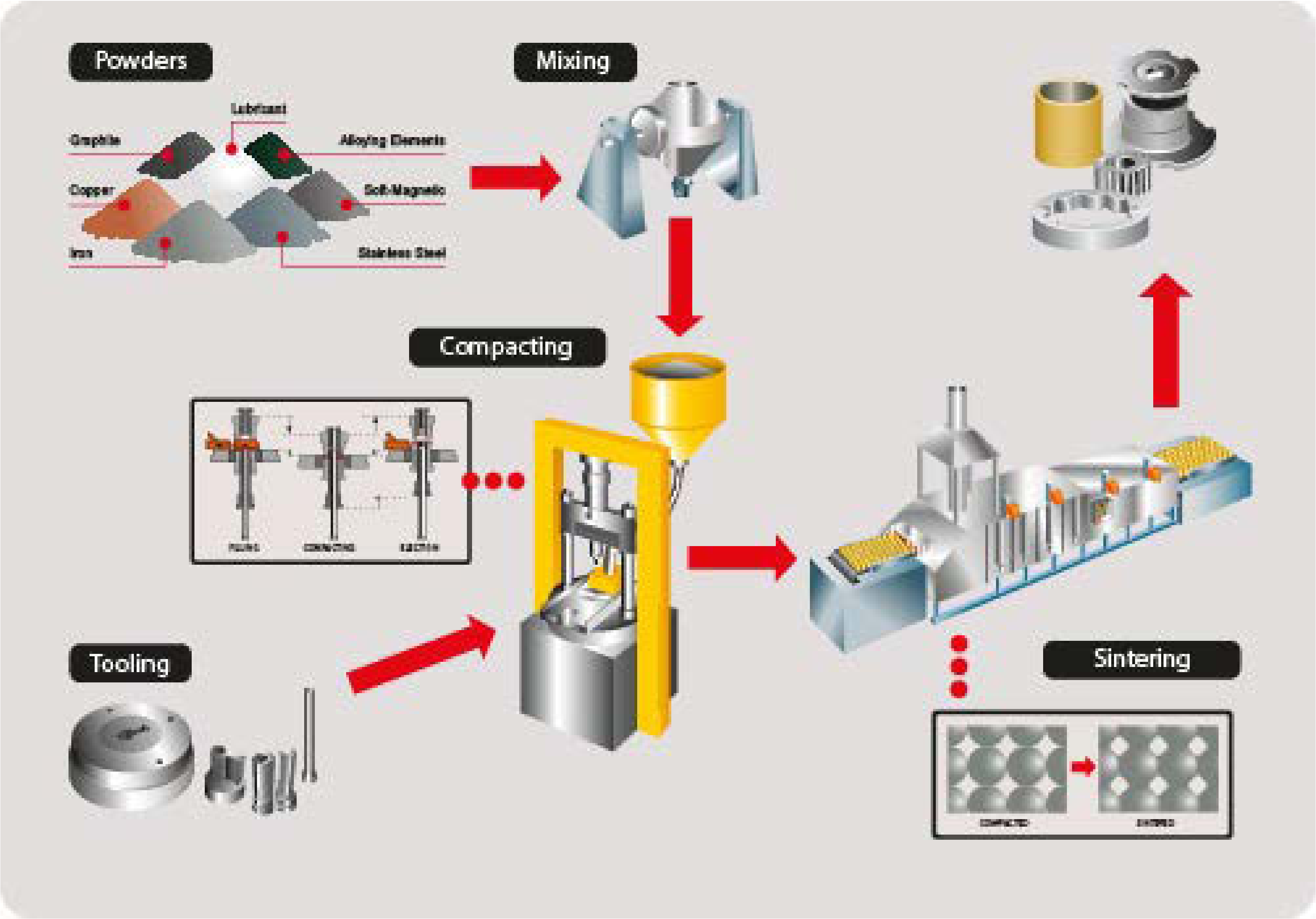


CCM Slot-Die Coating Process

Final CCM



Powder Metallurgy for GDL



GDL or Porous Transport Layer

Image source: http://erean.eu/wordpress/powder-metallurgy-and-permanent-magnets/

Porous Transport Layer = GDL

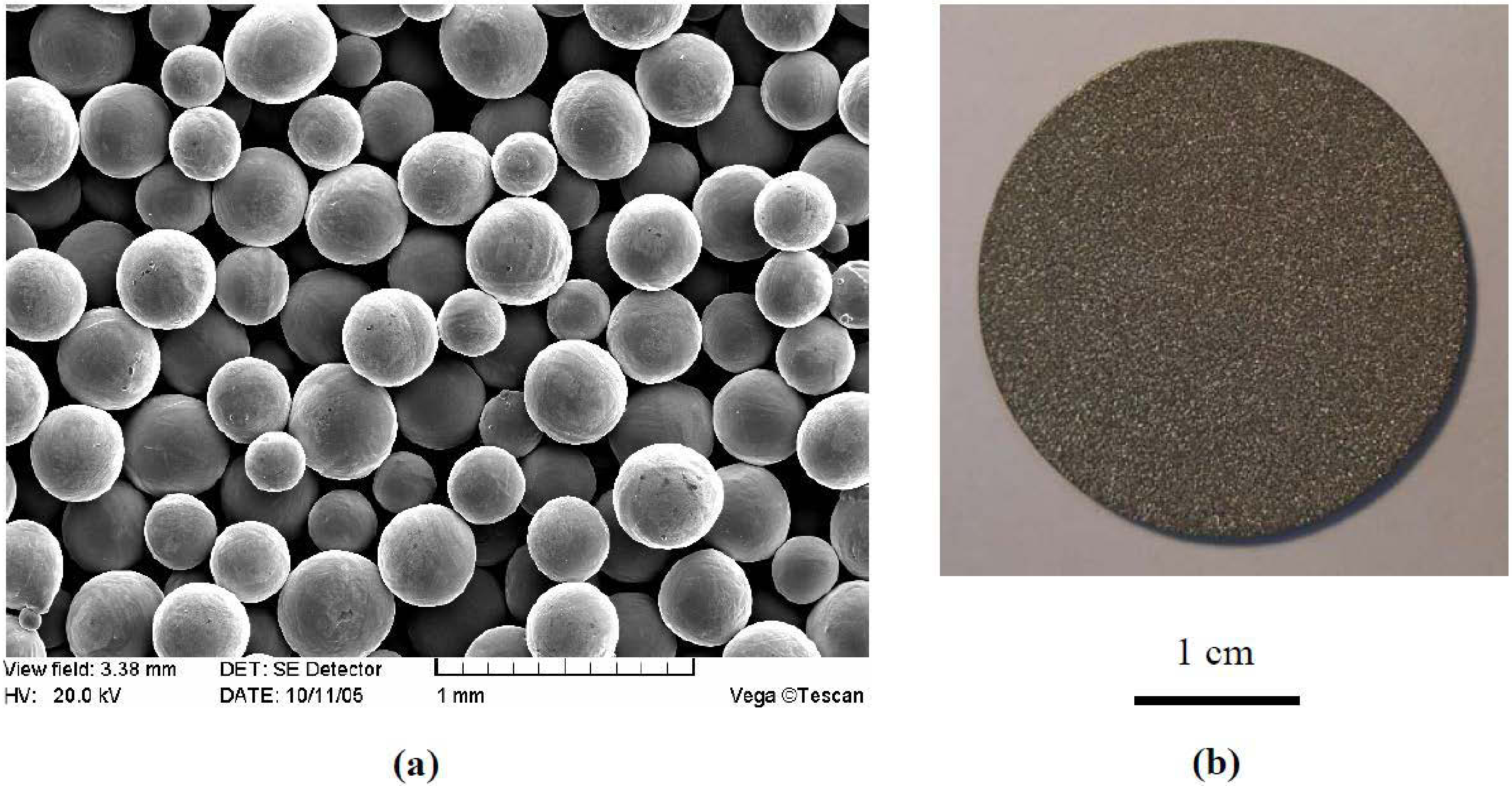
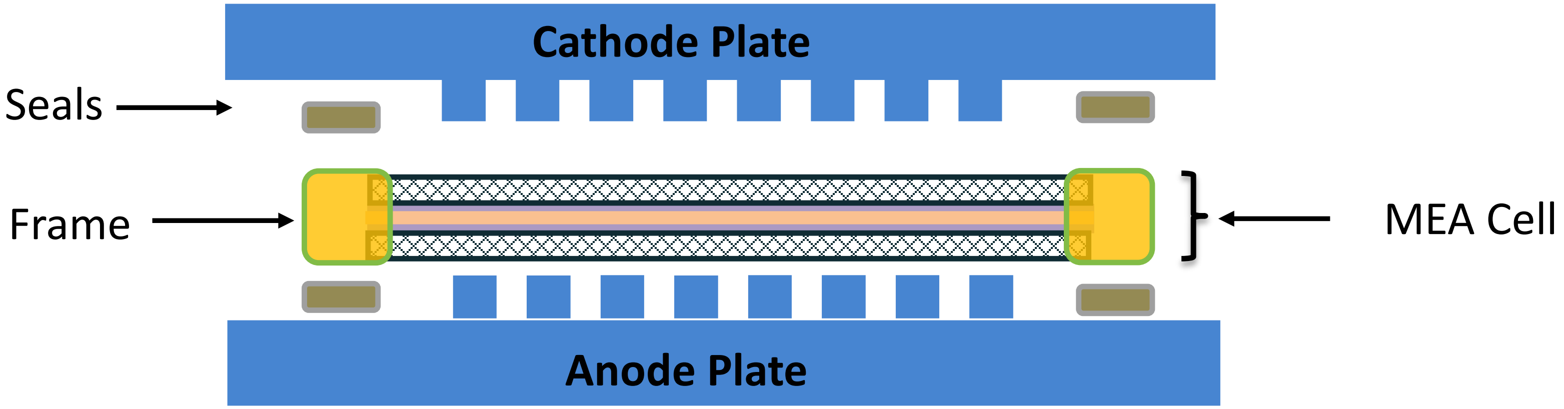
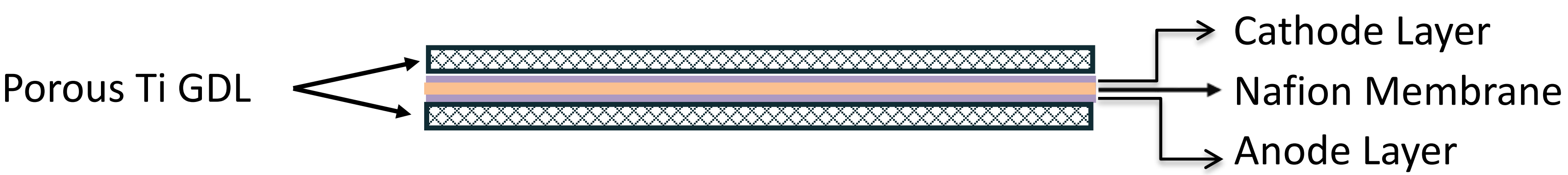


Fig. 2. SEM (a) and optical microscope (b) micrographs of a porous current collectors made of sintered titanium spherical-particles.

Grigoriev et al., 2007

Proposed Cell/Plates/Seal Structure

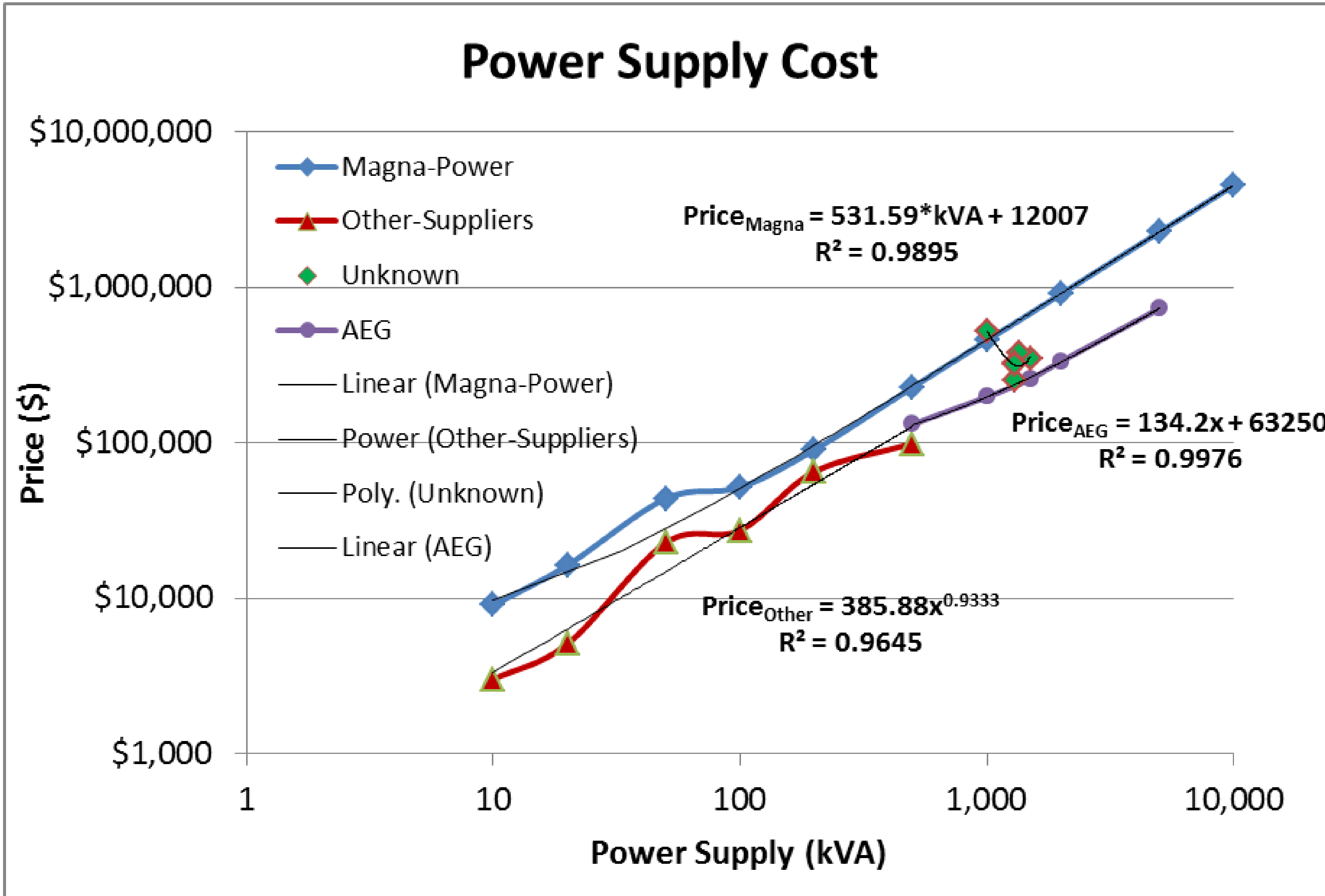




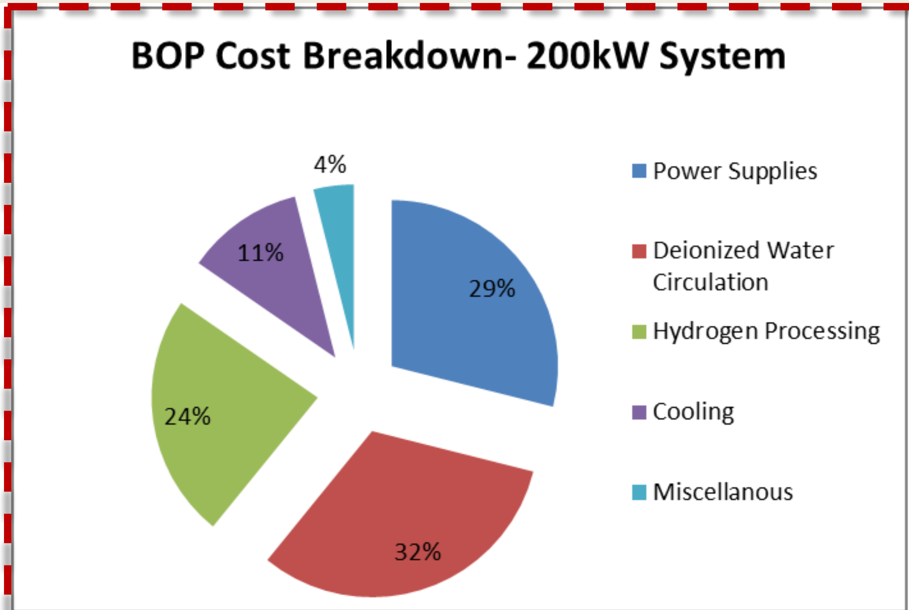
Balance of Plant Cost (Parts Only)

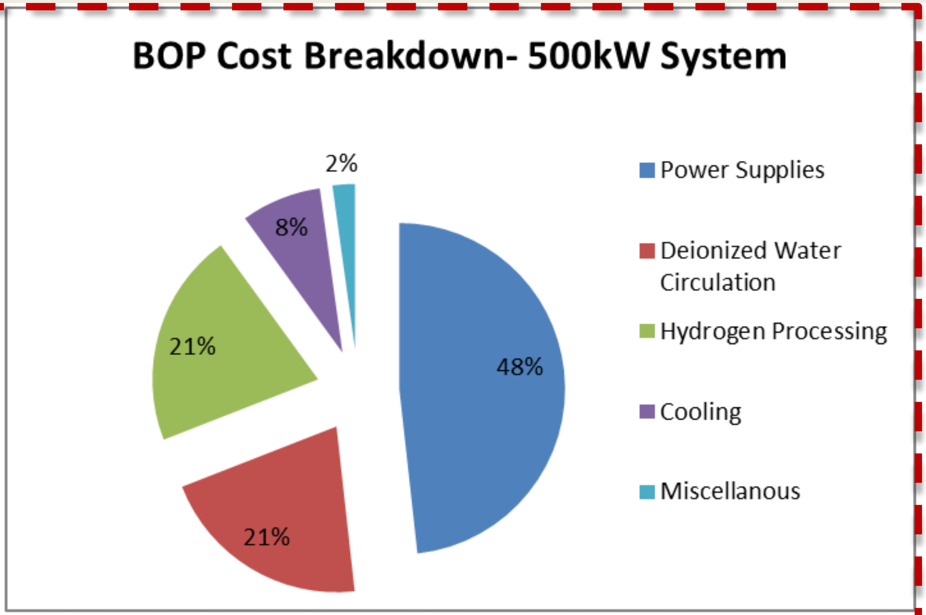
	System Size kW		10	20	50	100	200	500	1,000	2,000	5,000	10,000
			Baseline Cost ($)									
System	Subsystem	Sizing Exponent (if	10 kW	20 kW	50 kW	100 kW	200 kW	500 kW	1 MW	2 MW	5 MW	10 MW
Power Supplies	Power Supply	Quote (AEG)	$3,000	$5,080	$22,733	$27,331	$44,000	$132,000	$198,000	$335,500	$734,250	$1,405,250
	DC Voltage Transducer	Quote	$225	$225	$225	$225	$225	$225	$225	$225	$225	$225
	DC Current Transducer	Quote	$340	$340	$340	$340	$340	$340	$340	$340	$340	$340
	Total		**$3,225**	**$5,305**	**$22,958**	**$27,556**	**$44,225**	**$132,225**	**$198,225**	**$335,725**	**$734,475**	**$1,405,475**
Deionized Water Circulation	Oxygen Separator Tank	Quote	$10,000	$10,000	$10,000	$10,000	$20,000	$20,000	$40,000	$80,000	$160,000	$320,000
	Circulation Pump	Quote	$409	$647	$1,538	$3,349	$7,053	$10,000	$10,962	$20,000	$40,000	$80,000
	Polishing Pump	Quote	$1,619	$2,071	$2,071	$2,289	$2,289	$2,500	$5,000	$10,000	$20,000	$40,000
	Piping	0.30	$3,807	$4,687	$6,170	$7,597	$10,000	$12,311	$15,157	$18,661	$24,565	$30,243
	Valves, Instrumentation	0.30	$2,855	$3,516	$4,628	$5,697	$7,500	$9,234	$11,368	$13,995	$18,423	$22,682
	Pressure, temperature, conductivity, flowmeter											
	Class I, Div 2, Group B rating drives up prices											
	Controls	0.60	$2,000	$2,000	$2,000	$2,000	$2,000	$3,031	$4,595	$6,964	$12,068	$18,292
	Total		**$20,691**	**$22,921**	**$26,407**	**$30,932**	**$48,842**	**$57,076**	**$87,082**	**$149,621**	**$275,056**	**$511,217**
Hydrogen Processing	Dryer Bed		$6,366	$6,366	$13,860	$13,860	$13,860	$25,000	$36,589	$73,178	$146,356	$292,712
	Hydrogen Separator	0.70	$1,051	$1,707	$3,241	$5,266	$10,000	$16,245	$26,390	$42,871	$81,418	$132,264
	Tubing	0.30	$1,904	$2,344	$3,085	$3,798	$5,000	$6,156	$7,579	$9,330	$12,282	$15,121
	Valves, Instrumentation	0.30	$1,904	$2,344	$3,085	$3,798	$5,000	$6,156	$7,579	$9,330	$12,282	$15,121
	Pressure, temperature, conductivity, flowmeter											
	Class I, Div 2, Group B rating drives up prices											
	Controls	0.60	$362	$549	$952	$1,443	$2,500	$3,789	$5,743	$8,706	$15,085	$22,865
	Total		**$11,586**	**$13,309**	**$24,223**	**$28,165**	**$36,360**	**$57,346**	**$83,880**	**$143,415**	**$267,424**	**$478,084**
Cooling	Plate heat exchanger		$9,000	$9,000	$9,000	$9,000	$9,000	$9,000	$10,525	$11,675	$14,742	$14,742
	Cooling pump	Quote (n=0.67)	$970	$1,169	$1,169	$1,500	$1,500	$2,387	$3,797	$6,042	$11,163	$17,761
	Valves, instrumentation	0.60	$2,000	$2,000	$2,000	$2,000	$2,000	$3,031	$4,595	$6,964	$12,068	$18,292
	Piping	0.60	$1,000	$1,000	$1,000	$1,000	$1,000	$1,516	$2,297	$3,482	$6,034	$9,146
	Dry cooler	0.45	$4,000	$4,000	$4,000	$4,000	$4,000	$5,464	$7,464	$10,196	$15,400	$21,037
	Total		**$16,970**	**$17,169**	**$17,169**	**$17,500**	**$17,500**	**$21,398**	**$28,679**	**$38,360**	**$59,408**	**$80,979**
Miscellanous	Valve air supply – nitrogen or compressed air	n/a	$2,000	$2,000	$2,000	$2,000	$2,000	$2,000	$2,000	$2,000	$2,000	$2,000
	Ventiliation and safety requirements	n/a										
	Combustible gas detectors	n/a	$2,000	$2,000	$2,000	$2,000	$2,000	$2,000	$2,000	$2,000	$2,000	$2,000
	Exhaust ventiliation	n/a	$2,000	$2,000	$2,000	$2,000	$2,000	$2,000	$2,000	$2,000	$2,000	$2,000
	Total		**$6,000**	**$6,000**	**$6,000**	**$6,000**	**$6,000**	**$6,000**	**$6,000**	**$6,000**	**$6,000**	**$6,000**
	Grand Total ($)		**$58,472**	**$64,704**	**$96,758**	**$110,153**	**$152,927**	**$274,045**	**$403,865**	**$673,120**	**$1,342,363**	**$2,481,754**
	Cost ($/kW)		**$5,847**	**$3,235**	**$1,935**	**$1,102**	**$765**	**$548**	**$404**	**$337**	**$268**	**$248**

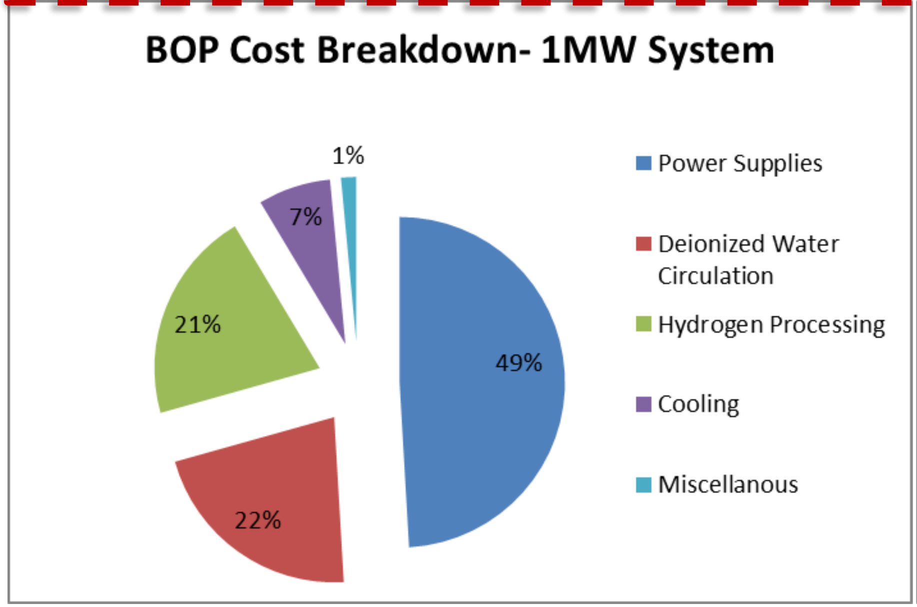
Power Supply Cost

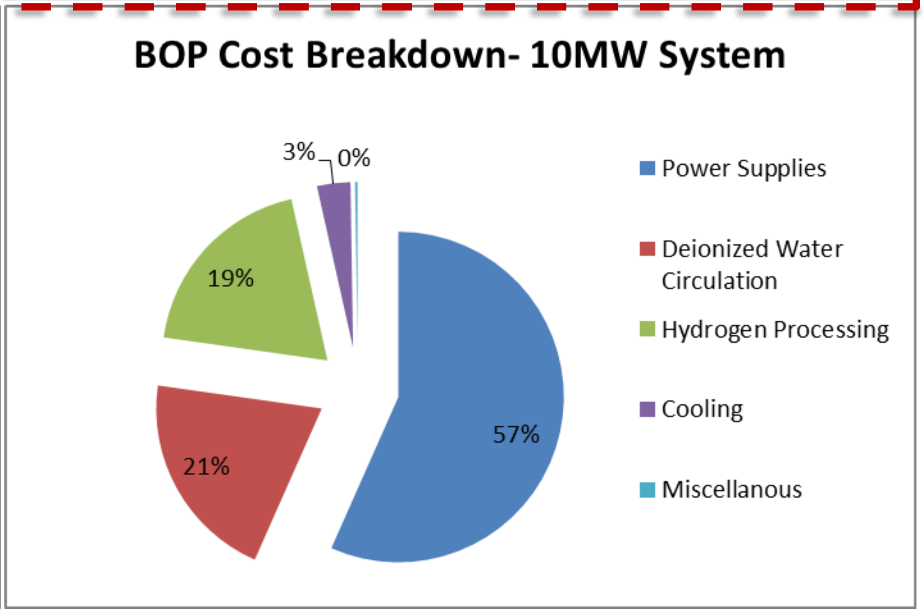


Balance of Plant Cost (Parts Only)









Alkaline Electrolysis

Alkaline Electrolyzer Stack

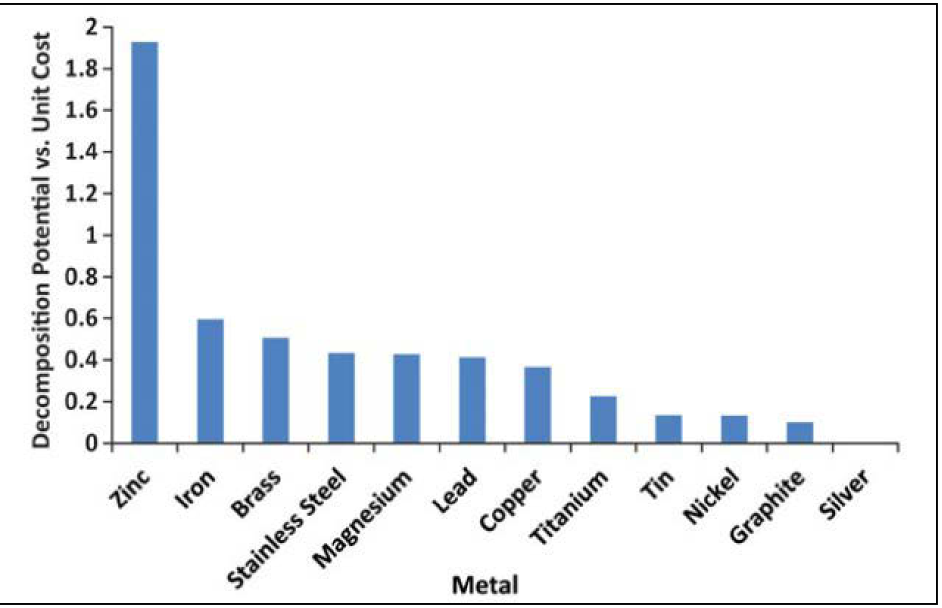
Cells are assembled electrically in series, hydraulically in parallel.

Picture of Hydrogenics Alkaline Electrolyzer

Commercial Alkaline Electrolyzers

	Manufacturer	Pure Energy Center	Hydrogenics	Hydrogenics	Hydrogenics	Units
	Model Number		HySTAT 15	HySTAT 30	HySTAT 60	
System	Electrolysis type	Alkaline	Alkaline	Alkaline	Alkaline	
	Rated stack Consumption	22.30	145.00	270.00	515.00	kW
	Electrolyte		H_2O+ 30% KOH	H_2O+ 30% KOH	H_2O+ 30% KOH	
	Hydrogen purity (dep. on operating point):	99.3-99.8	99.9	99.9	99.9	%
	System Effciency	5.58	4.90	5.20	4.90	kWh/Nm^3
	Net Prodution Rate	4	6 to 15	12 to 30	24 to 60	Nm^3/h
	Net Prodution Rate (scfh)		227 to 570	456 to 1140	912 to 2280	scfh
	Net Prodution Rate (kg/day)		13 to 32	26 to 65	52 to 130	kg/day
	kWh per kg ratio	62.08	54.52	57.86	54.52	kWh//kg
	Turndown Ratio	10-100%				%
	Output pressure	up to 12 bar	10	10	10	bar
	Feed Water	Deionized water				
	Fresh water demand:					ltr / Nm³ H2
	Inlet water pressure					barg
	Relative Humidity		<95	<96	<96	%
	Power Supply	400 VAC; 50 Hz			3*400 VAC 50 Hz	
	Cooling strategy	Air or liquid	Water cooled	Water cooled	Water cooled	
	Operating Temperature	5-35				°C
	Certification	CE Approved				
Other Specs	Other Specs					
	Dimensions	1.65	6		3.22X1.81X2.53	mXmXm
	Weight	260	3800			kg

Electrode Materials

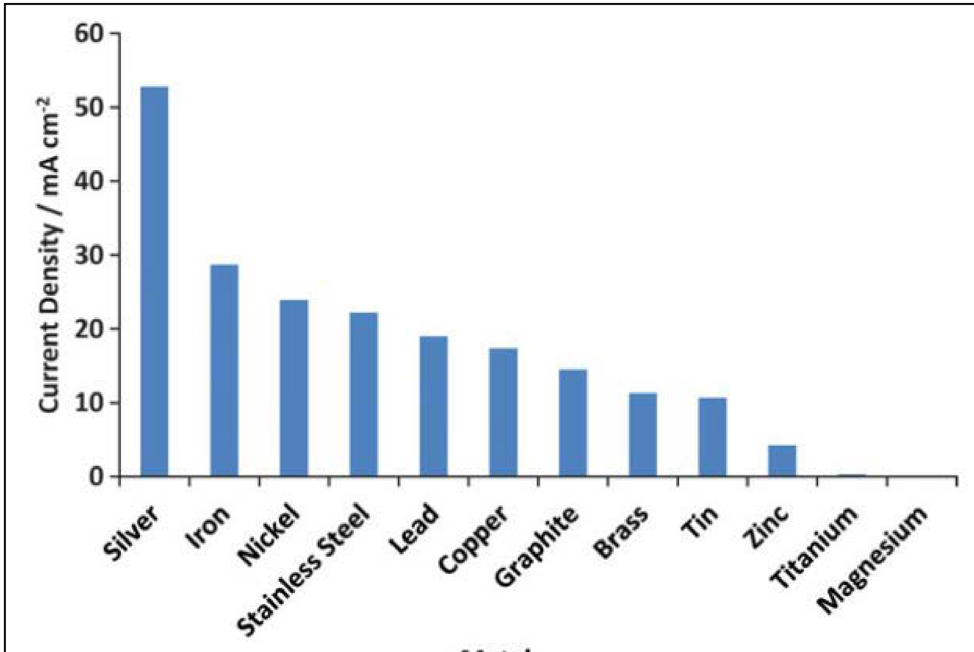


- **<u>Decomposition (corrosion) to cost ratio</u>**

➔ Zinc, iron and brass would perform better than other metals

- From the **<u>current density</u>** perspective

➔ Silver, iron and nickel would perform better than other metals



Symes et al., 2013

Alkaline Electrolyzer Power Density

Alkaline Water Electrolysis

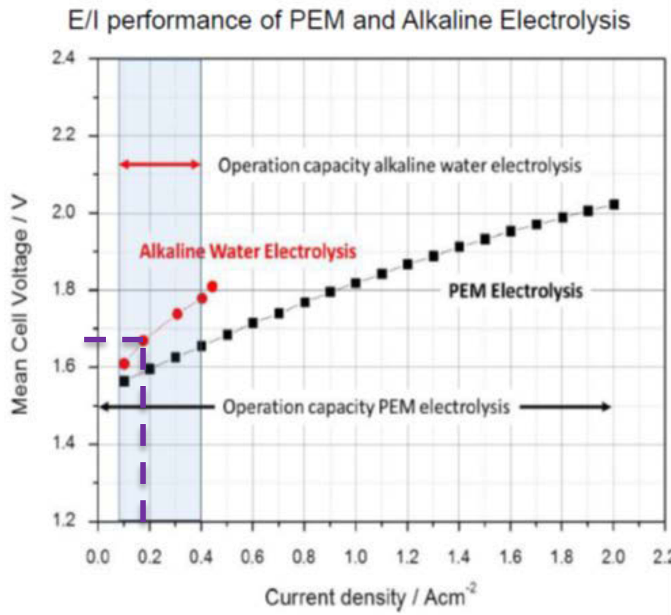
EMPA Materials Science & Technology

Advantages:

- Well developed technology
- Use of non-noble catalysts
- Long-term stability
- Units up to 750 Nm³/h (3,4 MW)

Challenges:

- Increase the current density
- Extend partial load capability
- Dynamics of the overall system
- Long term stable diaphragm



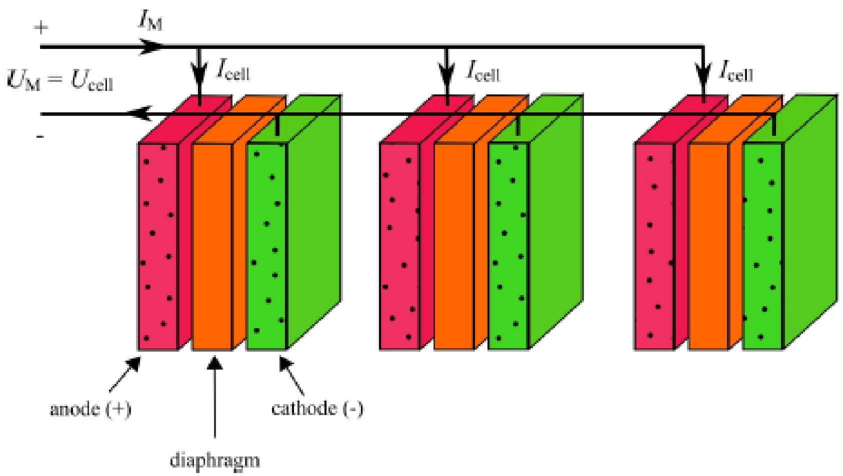
Source: Mergel, J; Carmo M, Fritz, D (2013). "Status on Technologies for Hydrogen Production by Water Electrolysis". In Stolten, D. Transition to Renewable Energy Systems. Weinheim: Wiley-VCH.

Current density	0.200	A/cm²
Reference voltage	1.68	V
Power density	0.336	W/cm²

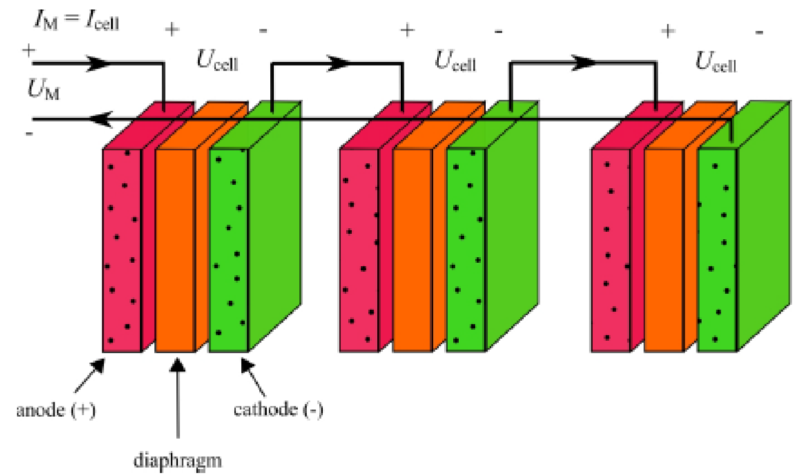
Current density			Today	2015	2020	2025	2030
A/cm²	Alkaline	Central	**0.3**	**0.4**	**0.7**	**0.7**	**0.8**
		Range	0.2 - 0.4	0.2 - 0.7	0.3 - 1.0	0.5 - 1.0	0.6 - 1.0
	PEM	Central	**1.7**	**1.9**	**2.2**	**2.4**	**2.5**
		Range	1.0 - 2.0	1.2 - 2.2	1.6 - 2.5	1.6 - 2.8	1.6 - 3.0

Alkaline Electrolyzer Configuration

Monopolar



Bipolar



NEO-CARBON ENERGY

14 10.2.2016 Joonas Koponen

LUT Lappeenranta University of Technology

Zero Gap Cell Design

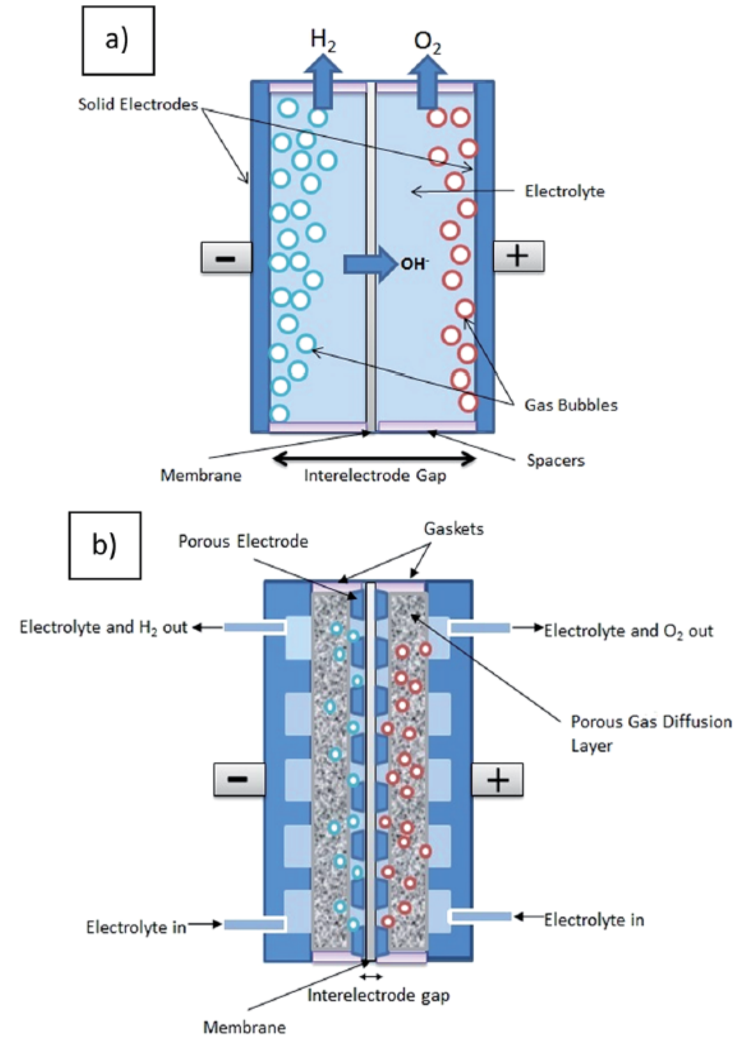


Fig. 1 (a) Standard setup, (b) zero gap setup – showing the principal differences in design, porous electrodes are pressed either side of the gas separator to reduce the inter-electrode gap, and a conducting gas diffusion layer provides an electrical connecting from the electrodes to the bipolar current collector.

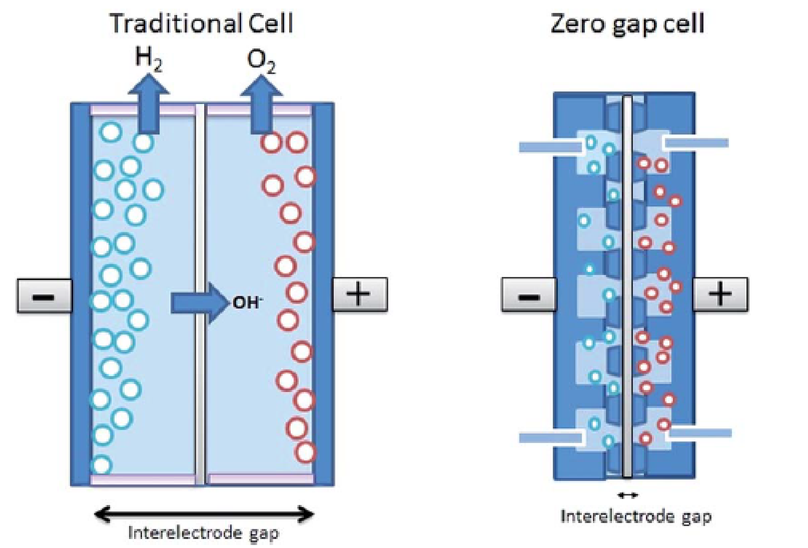


Fig. 4 Schematic showing reduction of inter-electrode gap from employing a zero gap cell design. This significantly reduces the overall cell resistance, increasing performance, particularly at high current densities. Note the loss in direct surface area between the pates due to the bubbles in the conventional design.

Phillips and and Dunnill, 2016

Stack Components

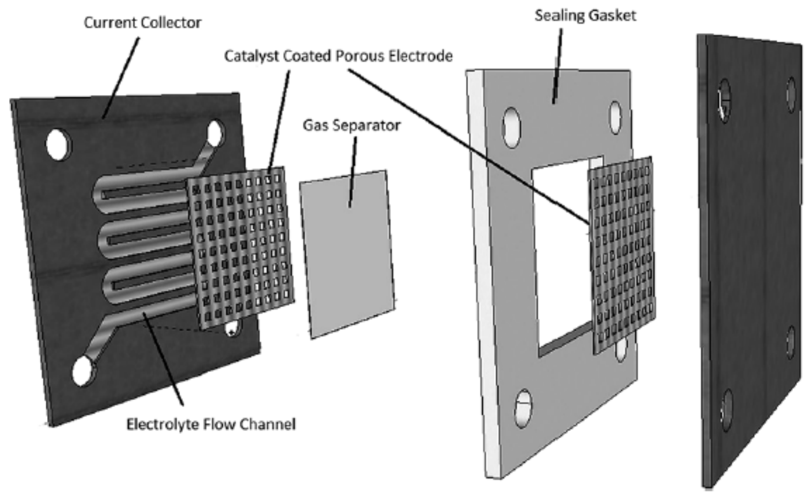


Fig. 7 3D schematic of a catalyst coated substrate zero gap cell, the two porous electrodes are individually coated with catalysts, and are pressed onto either side of the gas separator. The flow channels in the current collectors permit easily supply and removal of reactants/ products.

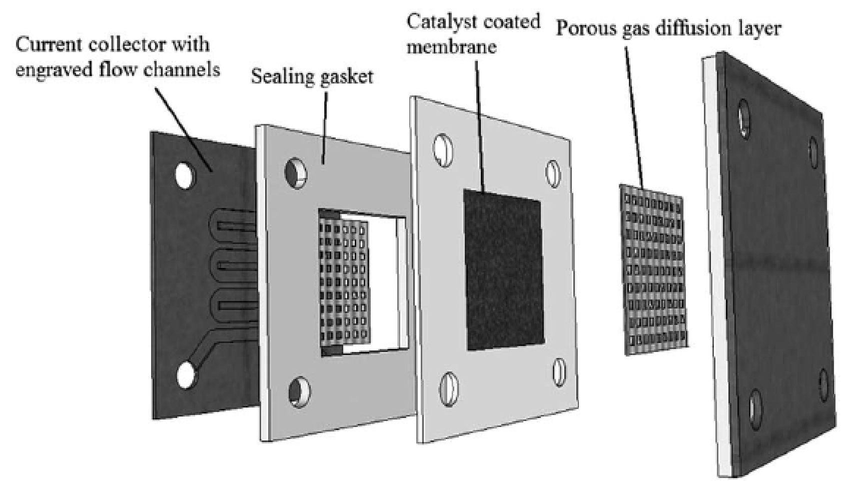


Fig. 9 Cell components for the catalyst coated membrane set-up. The catalyst is deposited directly onto the membrane, and the porous gas diffusion layers provide an electrical connection to the current collecting plate, whilst permitting the removal of produced gases.

- Catalyst coated substrate (CCS) design eliminates the need for gas diffusion layers
- Bipolar plates (current collectors) with integrated flow fields, provide:
  - 1) path for electrolyte (in and out)
  - 2) efficient removal of product gases from the cell
  - 3) heat management

Phillips and Dunnill, 2016

Electrode Materials

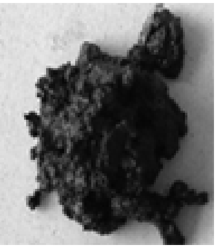
TABLE 1 | Comparison of HER Catalysts

Electrode	Performance	Conditions	References
Pt/C	0.6 mA cm^{-2} exchange current density	0.1 M KOH, thin film	Ref 31
Polished Ni	422 mV overpotential at 75 A cm^{-2}	0.5 M KOH, SCE, 3.14 mm^2 disk electrode	Ref 60
Co/C	1.1×10^{-2} mA cm^{-2} exchange current	0.1 M NaOH w/o ME nanoflakes	Ref 34
Ni_1Co_9/C	9.1×10^{-3} mA cm^{-2} exchange current	0.1 M NaOH w/o ME nanoflakes	Ref 34
Raney Ni	100 mV overpotential at 500 mA cm^{-2}	28 wt% KOH, 80°C	Ref 47
Ni–Cr Raney	80 mV overpotential at 500 mA cm^{-2}	28 wt% KOH, 80°C	Ref 47
$Ni_{64}W_{36}$	1.6×10^{-6} mA cm^{-2} exchange current density	0.1 M NaOH	Ref 51
$MmNi_{3.3}Co_{0.75}Mn_{0.4}Al_{0.27}$	88 mV overpotential at 200 mA cm^{-2}	Ni foam substrate and Ni–Mo coating, 30 wt% KOH	Ref 54
$LaNi_{4.9}Si_{0.1}$	84 mV overpotential at 200 mA cm^{-2}	Ni foam substrate and Ni–Mo coating, 30 wt% KOH	Ref 54
Ti_2Ni	60 mV overpotential at 200 mA cm^{-2}	Ni foam substrate and Ni–Mo coating, 30 wt% KOH	Refs 12 and 54
$Ni_{60}Mo_{40}$	29 mA cm^{-2} 59 mV overpotential at 250 mA cm^{-2}	30 wt% KOH, 70°C, nanocrystalline fcc, mechanical alloyed	Ref 62
Ni–S	39.2 mA cm^{-2} 90 mV overpotential at 150 mA cm^{-2}	28 wt% NaOH, electrodeposited, thiourea	Ref 40
Fe–Mo	20.4×10^3 mA cm^{-2}	Fe(20%)–Mo(60%), 1 M NaOH, 25°C	Ref 57
Ni–(Ebonex-Ru)	597 mA cm^{-2} 156 mV at 100 mA cm^{-2}	$Ni–Ti_4O_7$–Ru, 1 M NaOH at 25°C	Ref 63
Pd/Au	NA	Pd/Au(111)	Ref 56
Ni–Sn	NA	Alloy coating deposited on Ni mesh	Ref 64
Ni–S–Co	70 mV at 150 mA cm^{-2}	80°C, electrodeposition	Ref 41
Ni_3Al	1.9 mA cm^{-2}	6 M KOH	Ref 36
Ni_3Al–Mo	13 mA cm^{-2}	6 M KOH	Ref 37
Ni-S–Mn	97.5 mA cm^{-2}	30% KOH, amorphous alloy	Ref 43
$Ni_{81}P_{16}C_3$	2.11 mA cm^{-2} 125.4 mV at 250 mA cm^{-2}	1 M NaOH, 25°C	Ref 39
$Ni_{62}Fe_{35}C_3$	24.5 mA cm^{-2} 112.6 mV at 250 mA cm^{-2}	1 M NaOH, 25°C	Ref 65
Ni–Co	29 mA cm^{-2}	0.5 M NaOH, 25°C, electrodeposited	Ref 66
$Fe_{94}P_4Ce_2$	0.075 mA cm^{-2}	1 M NaOH, 25°C	Ref 45

HER: Hydrogen Evolution Reaction

Table from Bodner et al., 2015

Raney nickel is an alloy of aluminum and nickel, which has subsequently had much of the aluminum removed through a leaching process with sodium hydroxide (NaOH). The remaining alloy has a very high surface area and also contains hydrogen gas (H_2) adsorbed on the nickel surface



Raney Nickel (Ra-Ni)

Image from: http://www.masterorganicchemistry.com/2011/09/30/reagent-friday-raney-nickel/

Membranes

Membrane	Ion Exchange Capacity	Conductivity (mS/cm)	Thickness	Cell Current Density† (mA/cm^2)	Manufacturer	Ref.
Tokuyama A201	1.68 ± 0.08	40	28 µm	400 @1.8V	Tokuyama, (Japan)	Bodner et al., (2015) Ren et al., (2014)
Nafion 117	0.91	90.6	178 µm	n/a	DuPont (USA)	Ren et al., (2014)
m-PBI poly(2,2-(*m*-phenylene)-5,5-bibenzimidazole)	n/a	100	50-60 µm	400 @2V	Danish Power Systems (Denmark), Advent (USA)	Kraglund et al., (2016)
Zirfon™ Perl UTP 500 (polyphenylene sulphide/zirconium oxide)		Ionic resistance≤0.3 $\Omega.cm^2$ at 30†	500 ± 50 µm	250 @2V	Agfa-Gevaert (Belgium)	
xxx						

† Assuming 30% KOH

Membrane

TABLE 2 | Comparison of Different AEMs for Alkaline Electrolysis Cells

Membrane	Conductivity	Current density	Cathode	Anode	High frequency resistance	Thickness	References
Zero gap diaphragm with 30 wt% KOH	54.3×10^{-2}/(Ωcm) at 25°C[a]	470 $mA\ cm^{-2}$ at 1.8 V, 50°C	Mo/Raney Ni	Co_3O_4/Raney Ni	NA	NA	Refs 19, [a]84
Tokuyama A201	0.04 $S\ cm^{-1}$ at 23°C[b]	399 $mA\ cm^{-2}$ at 1.8 V, 50°C	Pt black	IrO_2	0.23 $\Omega\ cm^2$ at 2.0 V, 50°C	28 μm	Refs 19, [b]85
Selemion AMV	$2.52 \times 10^{-1}\ S\ cm^{-1}$	90 mA/cm^{-2} at 2.0 V, 30°C	Ni/Zn/S coated Ni foam	Graphene oxide-coated NiO	NA	120 μm	Ref 61
QAPS	$>10^{-2}\ S\ cm^{-1}$	0.4 A/cm^{-2} at 1.8–1.85 V, 70°C	Ni–Mo	Ni–Fe	NA	70 μm	Ref 48
qPVB/Cl	2.7×10^{-2} S cm at 60°C	250 $mA\ cm^{-2}$ at 2.24 V, 55°C	Ni nano powder	$Cu_{0.7}Co_{2.3}O_4$	0.37 $\Omega\ cm^2$ at 60°C	70 μm	Ref 81
QA-ETFE[c], QPDTB ionomer	138.7 $mS\ cm^{-1}$[c] (ionomer: 0.059 $S\ cm^{-1}$ at 50°C)	100 $mA\ cm^{-2}$ at 1.9 V, 22°C	Ni nanopow-der	$Cu_{0.7}Co_{2.3}O_4$	0.85 $\Omega\ cm^2$ at 22°C full MEA resistance	88.4 μm[c]	Refs 83, [c]82
LDPE-g-VBC	17 $mS\ cm^{-1}$ at 60°C	300 $mA\ cm^{-2}$ at 2.1 V, 45°C**	NA	NA	0.3–0.43 $\Omega\ cm^2$ at 45°C	NA	Ref 80

**Data was taken from a diagram, since the values were not stated within the text.

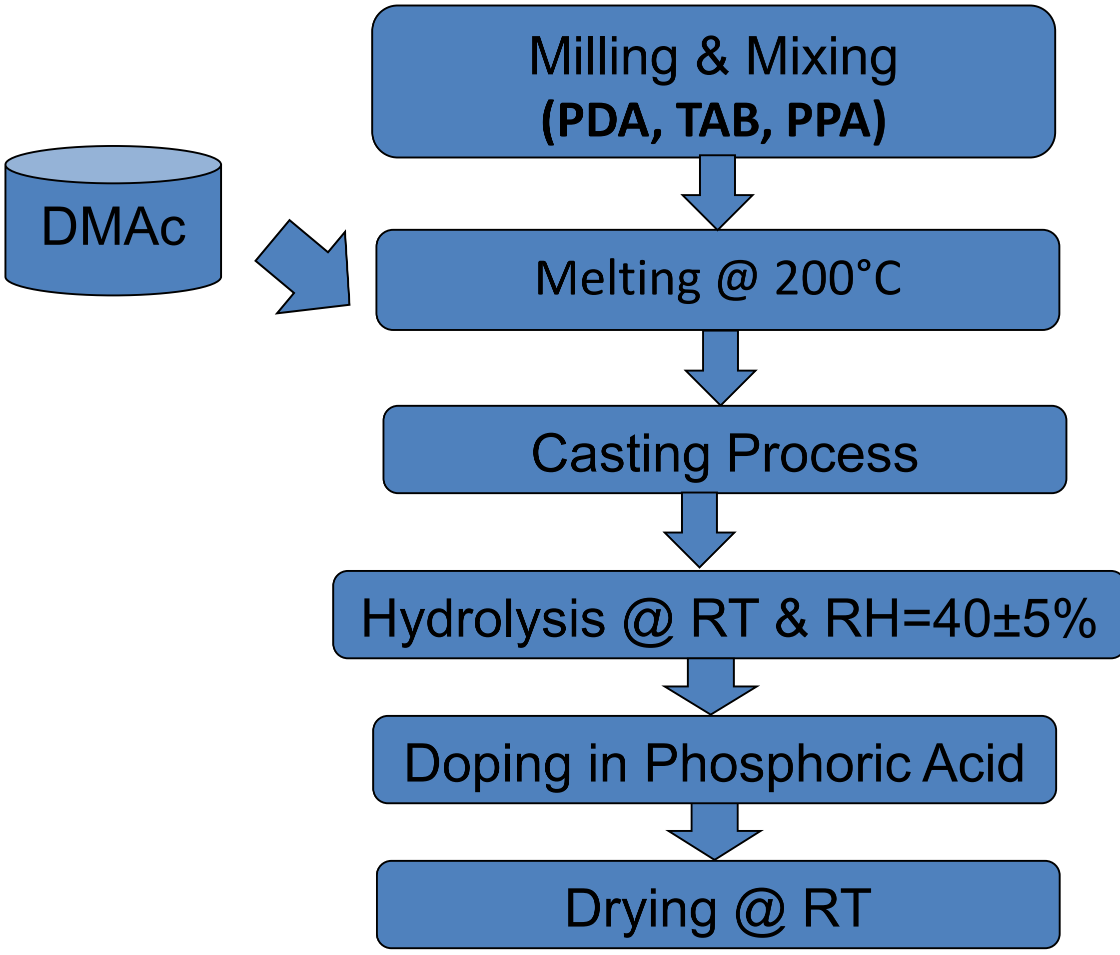
* This table is copied from Bodner et al., 2015

PBI-based Membrane - Preliminary

BOM- 1st Generation Monomers

Materials	Suppliers	Price
Pyridine dicarboxylic acids (2,4-, 2,5-, 2,6- and 3,5-PDA)	Sigma-Aldrich Chemical Co. Matrix Scientific Alpha Aeser Chemical Co.	\$126 for100mg \$91 for 25 g \$212 for 500 g
3,3′,4,4′-Tetraaminobiphenyl (TAB)	Sigma-Aldrich Chemical Co. TCI America Tetra-Hedron	\$250 for 25 g \$126 for 25 g \$380 for 100 g
Polyphosphoric acid (115%) (PPA)	Sigma-Aldrich Chemical Co.	\$60 for1 kg
Ammonia Hydroxide	Sigma-Aldrich Chemical Co.	\$340 for 6X2.5L
Distilled water	Sigma-Aldrich Chemical Co.	
Phosphoric Acid (Conc. 85% for doping)	Duda Energy	\$40 per gallon
Dimethylacetamide (DMAc)	Sigma-Aldrich Chemical Co. Alpha Aeser Chemical Co.	\$542 for 6L \$82.5 for 2.5L

Manufacturing of PBI-based Membrane



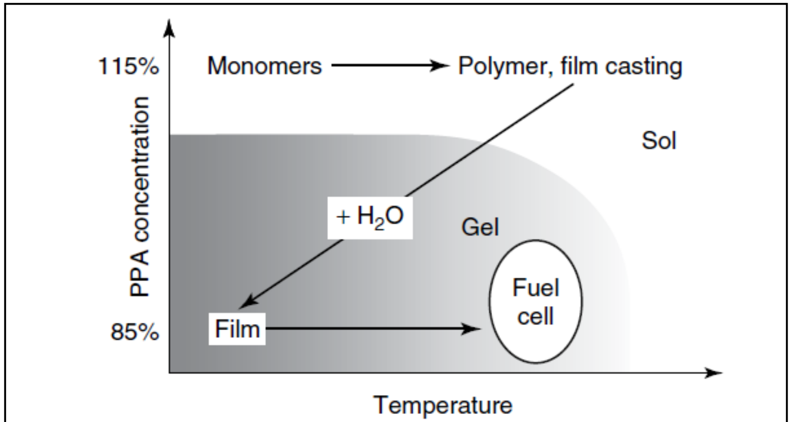
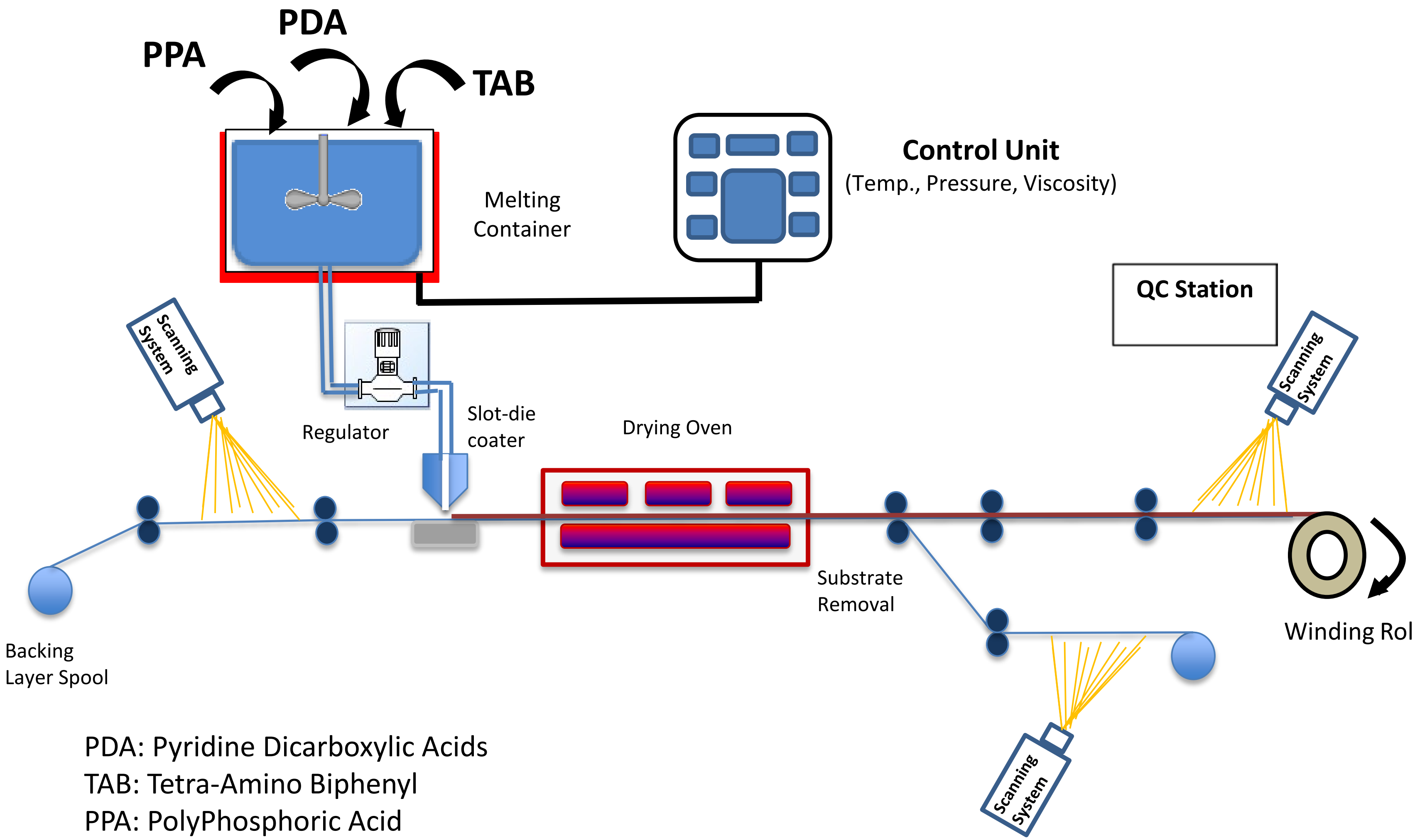


Figure 1. State diagram of the PPA sol–gel preparation process.

Image from Xiao et al., 2005

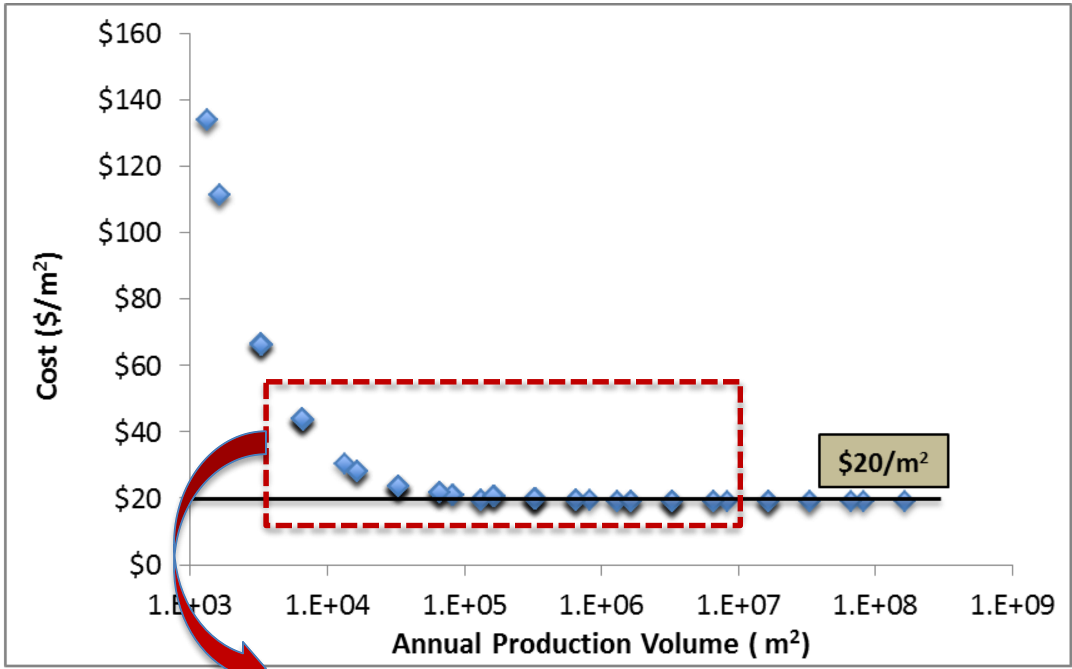
Casting Process

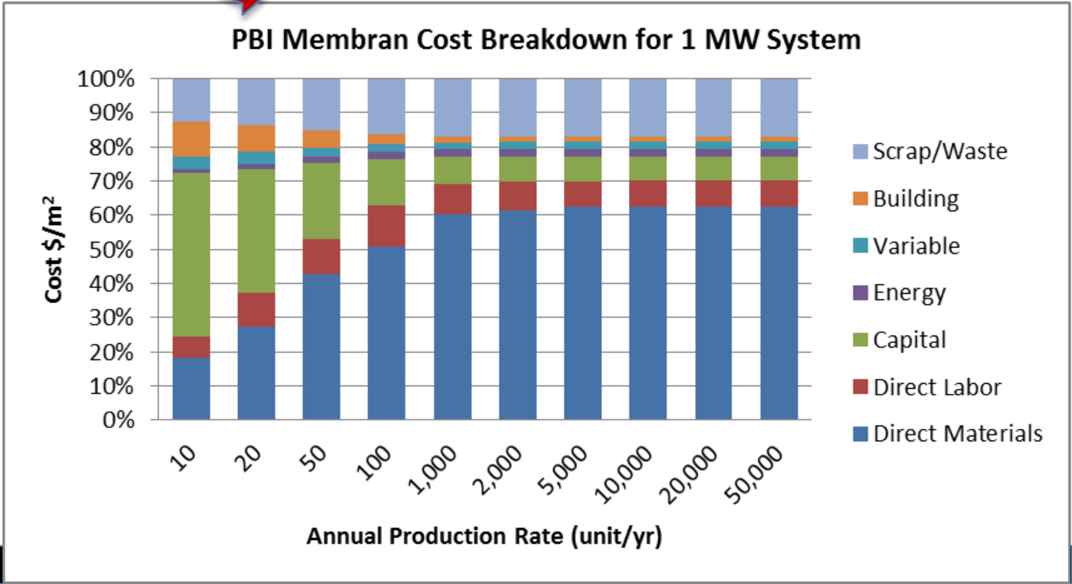


PDA: Pyridine Dicarboxylic Acids
TAB: Tetra-Amino Biphenyl
PPA: PolyPhosphoric Acid

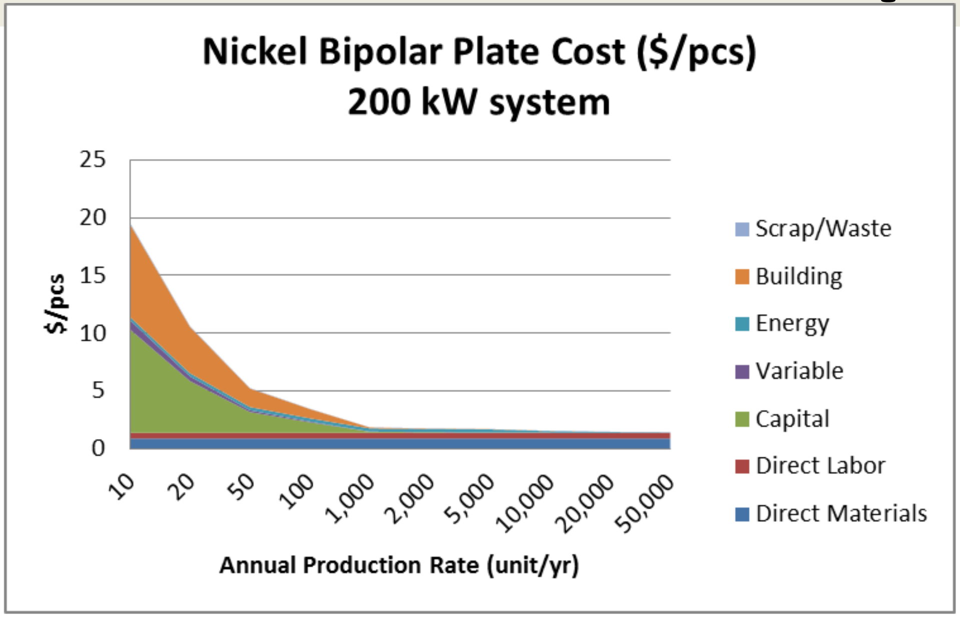
BPI Membrane Cost Analysis- Preliminary

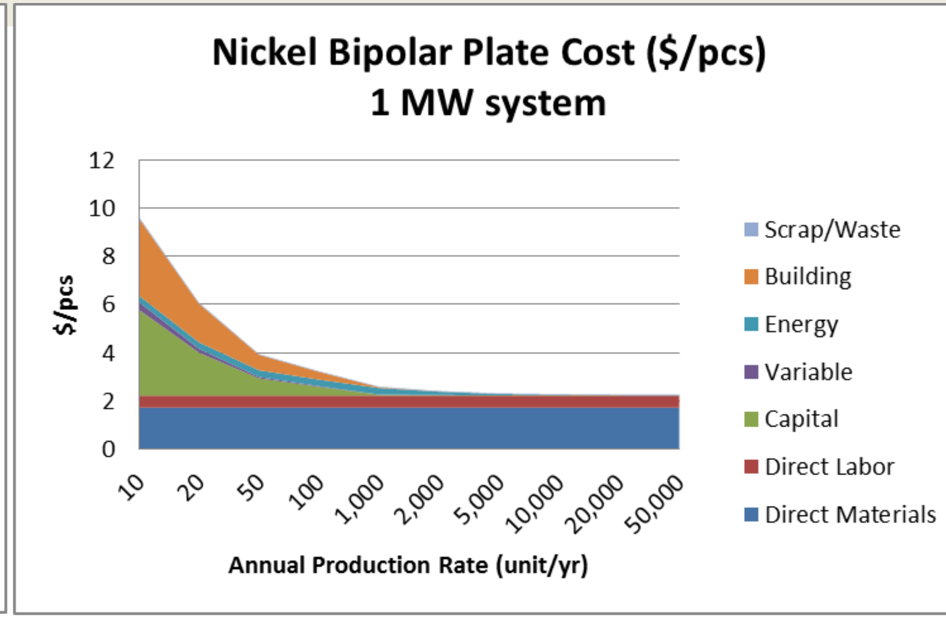
- Bill-of materials based on 1st generation materials (Xiao et al., 2003).
- Cost includes capital, building, operational, labor, material and scrap cost components.

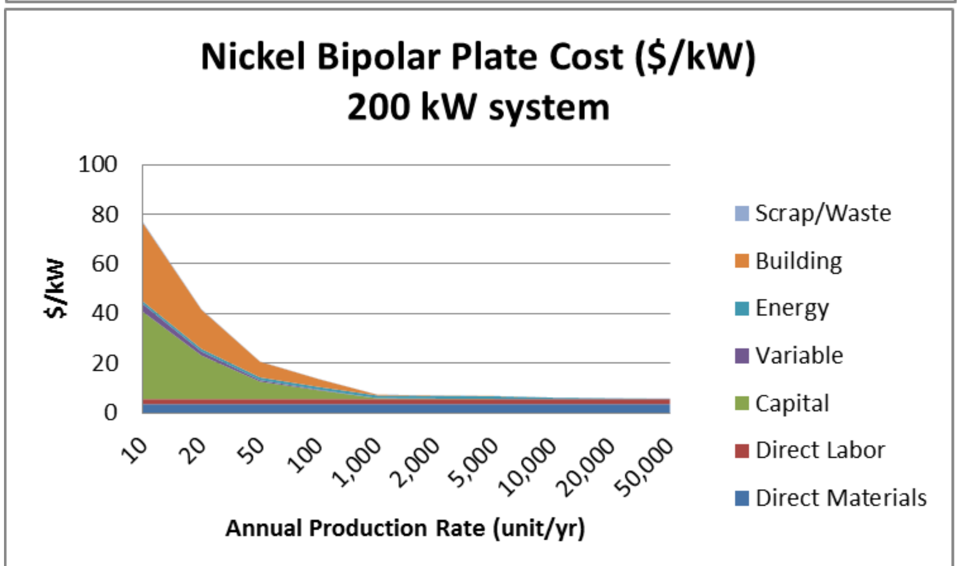


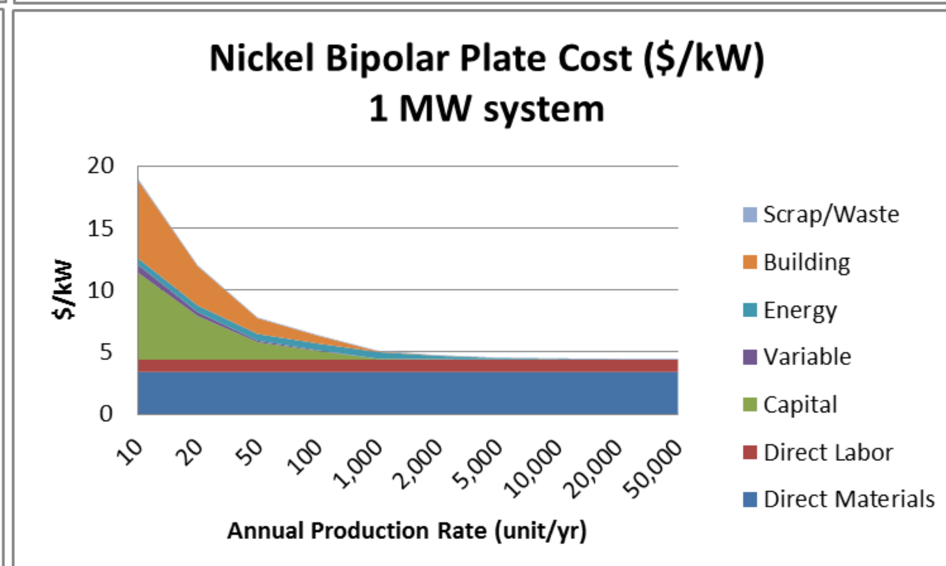


Nickel Bipolar Plates







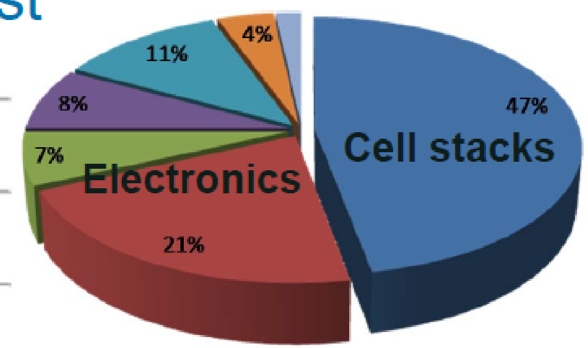


48 kg/day

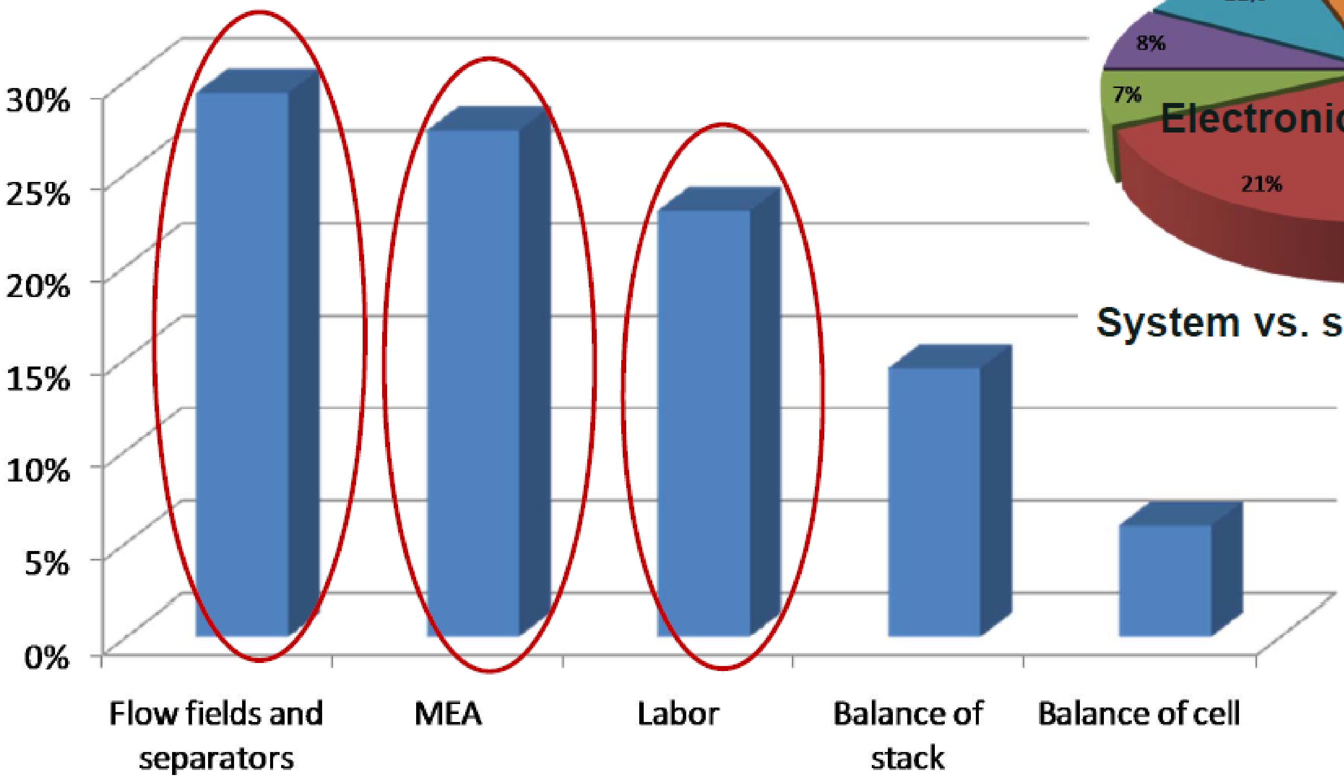
240 kg/day

Historical Cost Breakdown

- Flow field, membrane electrode assembly, and labor are high impact cost areas
- Catalyst represents ~6% of total cost



System vs. stack breakdown

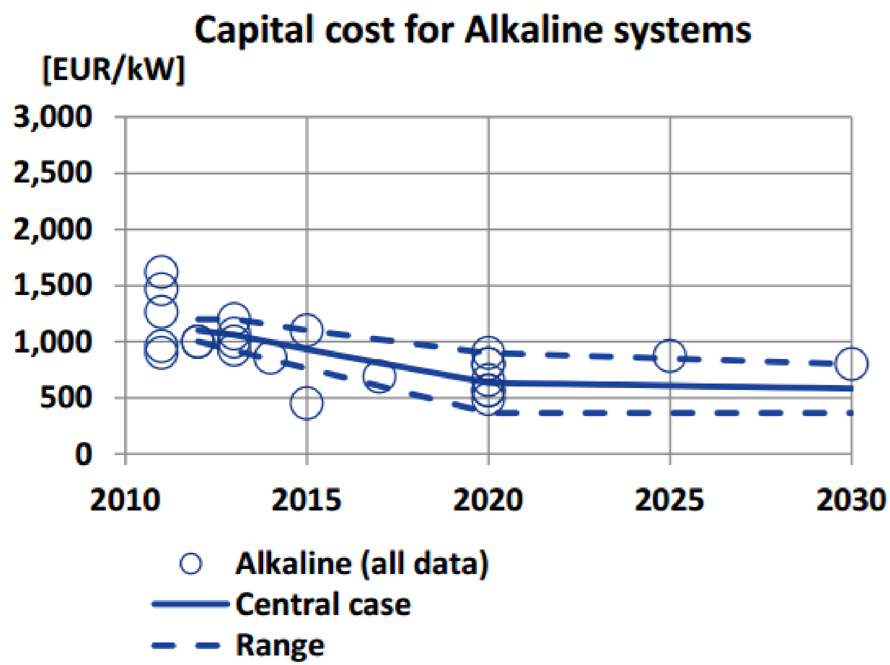


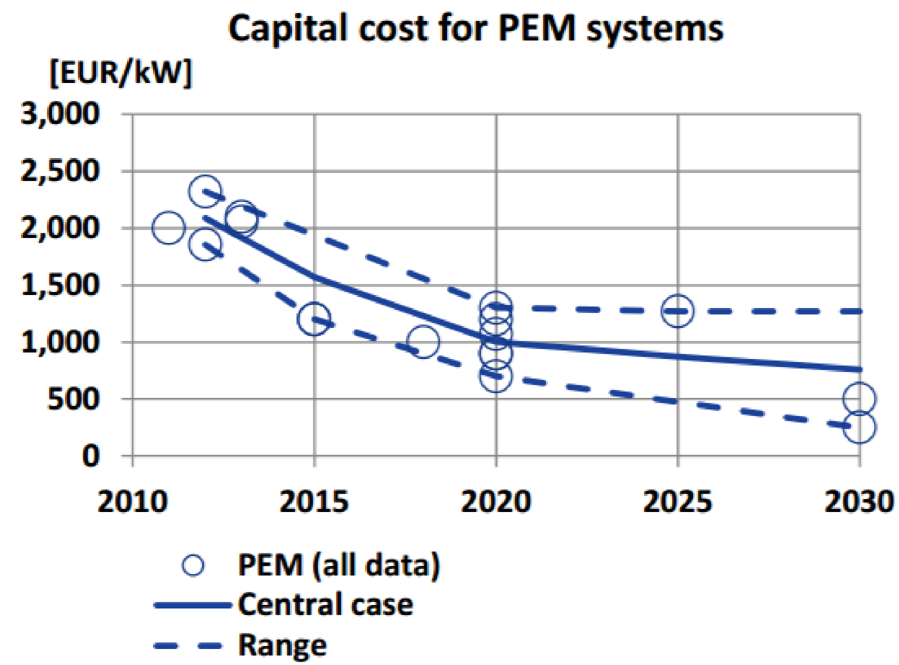
PROTON ON SITE

Page 2

Anderson, 2015

PEM and Alkaline Electrolyzer Capital Cost



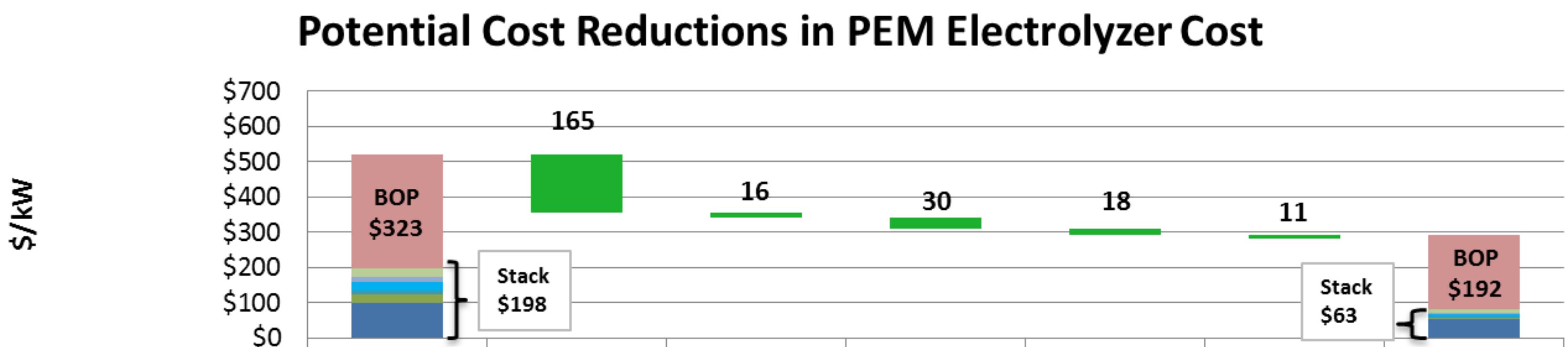


System cost [1]			Today	2015	2020	2025	2030
EUR/kW	Alkaline	Central	**1,100**	**930**	**630**	**610**	**580**
		Range	1,000 - 1,200	760 - 1,100	370 - 900	370 - 850	370 - 800
	PEM	Central	**2,090**	**1,570**	**1,000**	**870**	**760**
		Range	1,860 - 2,320	1,200 - 1,940	700 - 1,300	480 - 1,270	250 - 1,270

[1] incl. power supply, system control, gas drying (purity above 99.4%). Excl. grid connection, external compression, external purification and hydrogen storage

Bertuccioli et al. 2014

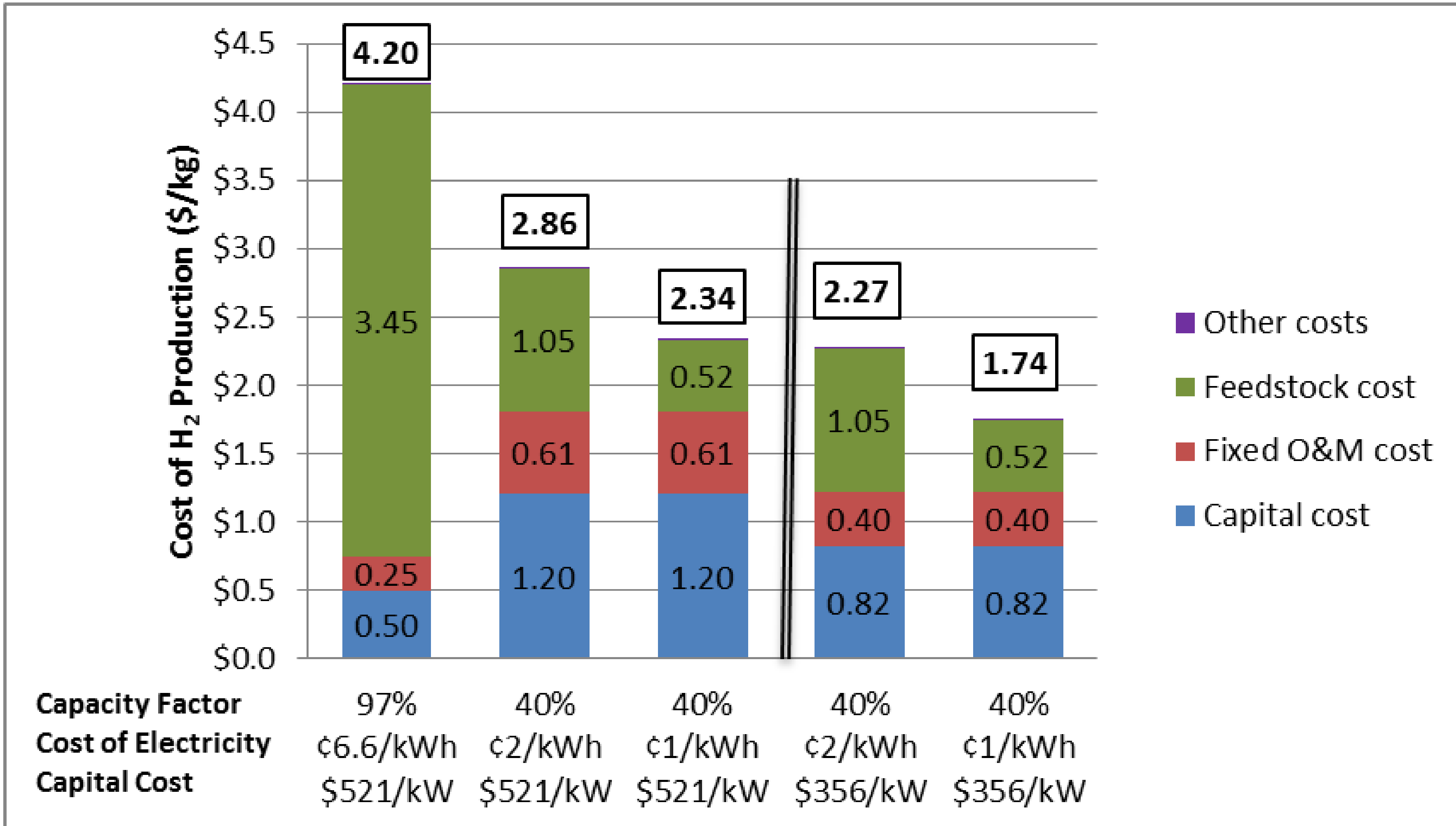
Waterfall Chart – Capital Cost



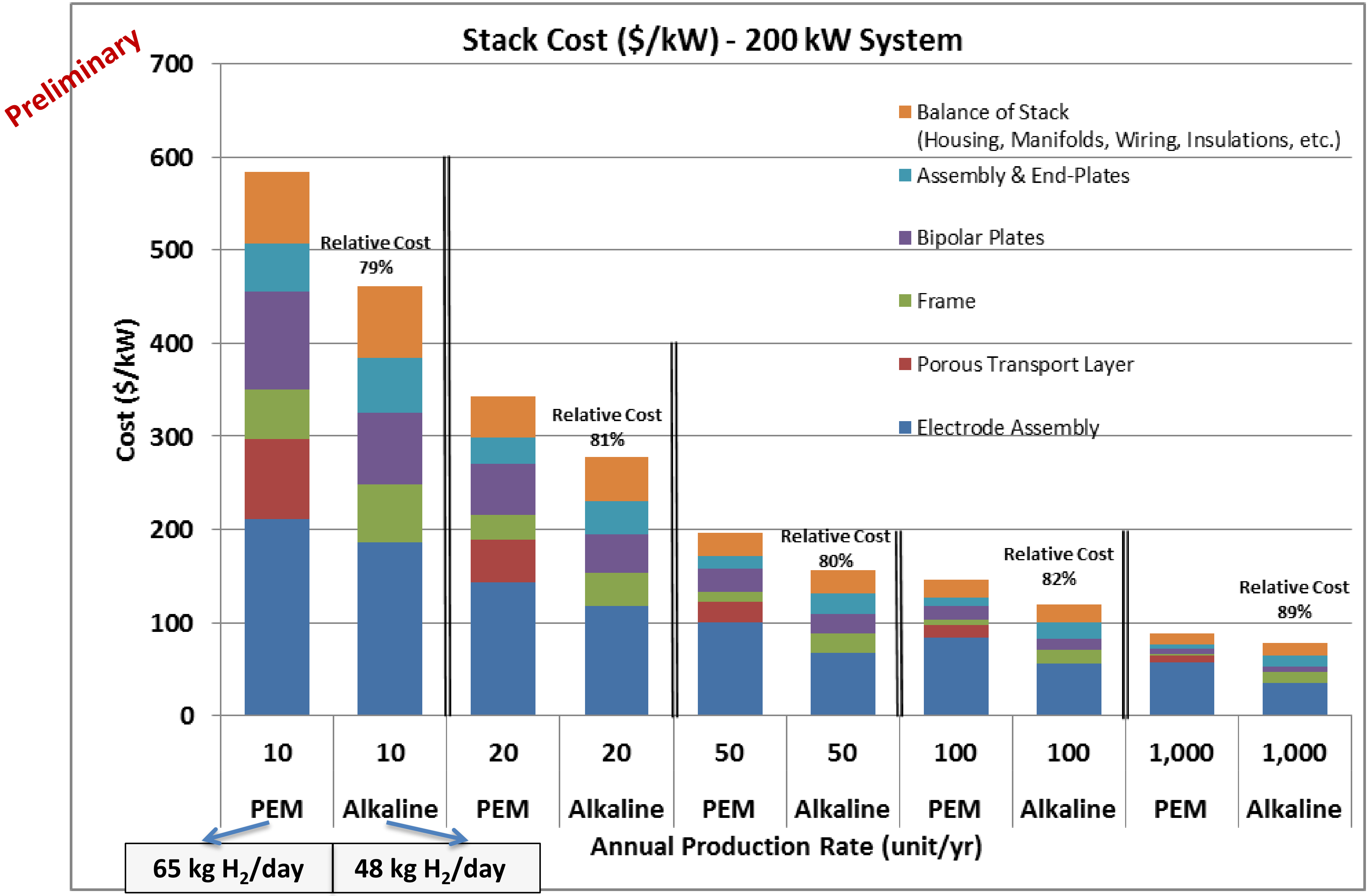
	Base Cost ($/kW)	Economies of Scale	Power Electronics Cost	Improvement in Power Density	Pt Loading	Membrane Cost	Final Cost ($/kW)
Delta		165	16	30	18	11	0
Bottom	0	356	340	310	291	281	281
BOP	$323	$0	$0	$0	$0	$0	$211
Balance of Stack	$26	$0	$0	$0	$0	$0	$10
Assembly & End-Plates	$13	$0	$0	$0	$0	$0	$4
Bipolar Plates	$25	$0	$0	$0	$0	$0	$5
Frame	$12	$0	$0	$0	$0	$0	$3
Porous Transport Layer	$22	$0	$0	$0	$0	$0	$6
CCM	$100	$0	$0	$0	$0	$0	$51

- Assumptions:
  - Economies of scale: cost of producing 100 unit/yr vs. 10 units/yr
  - Power electronics : 10% cost reduction
  - Improvement in power density: +20% (from 2.91 W/cm^2 to 3.50 W/cm^2)
  - Pt loading: reducing PGM loading from 11 g/m^2 to 5 g/m^2
  - Membrane cost: 20% cost reduction

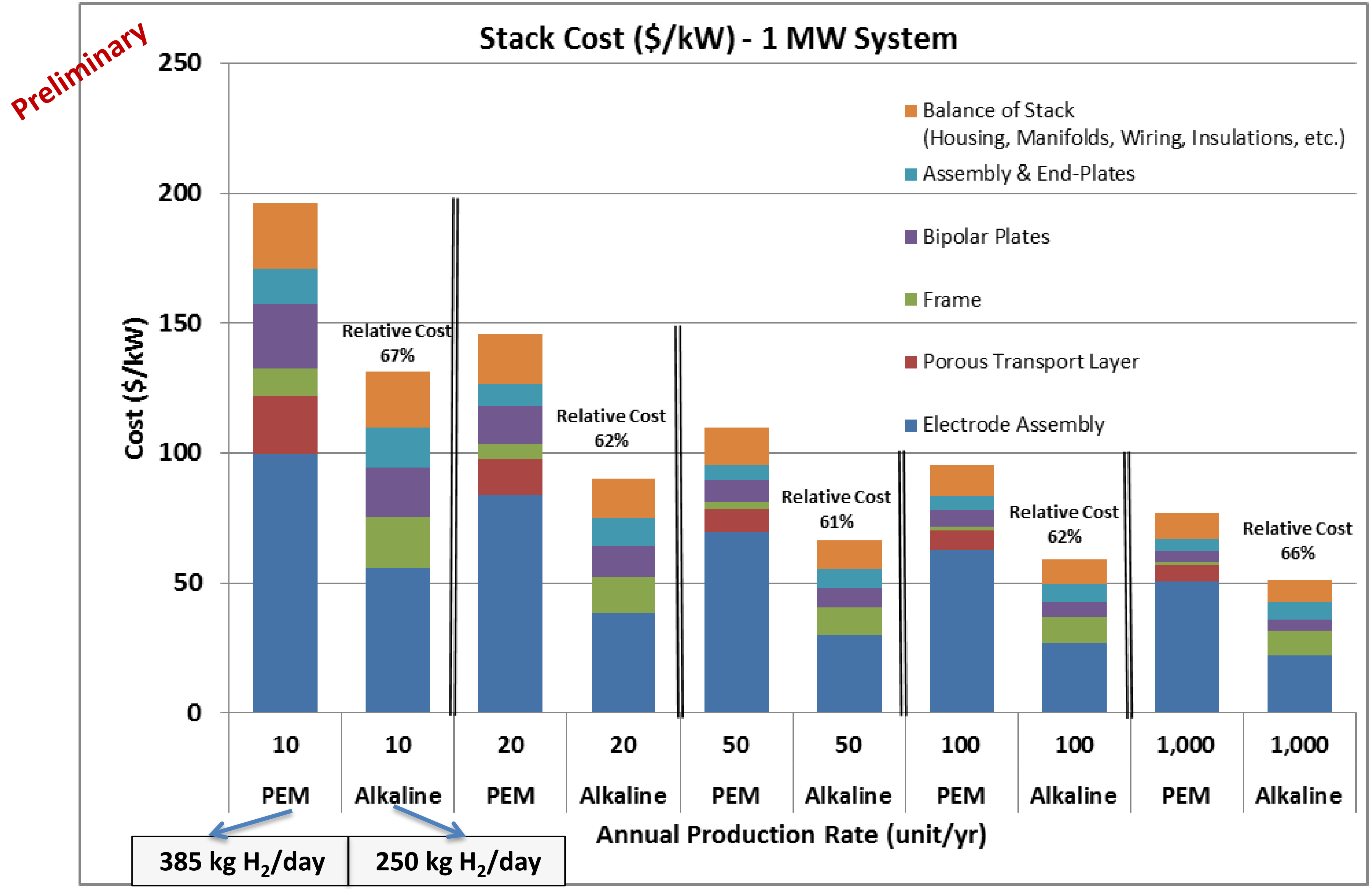
Effect of Electrolyzer Capital Cost on H_2 Cost



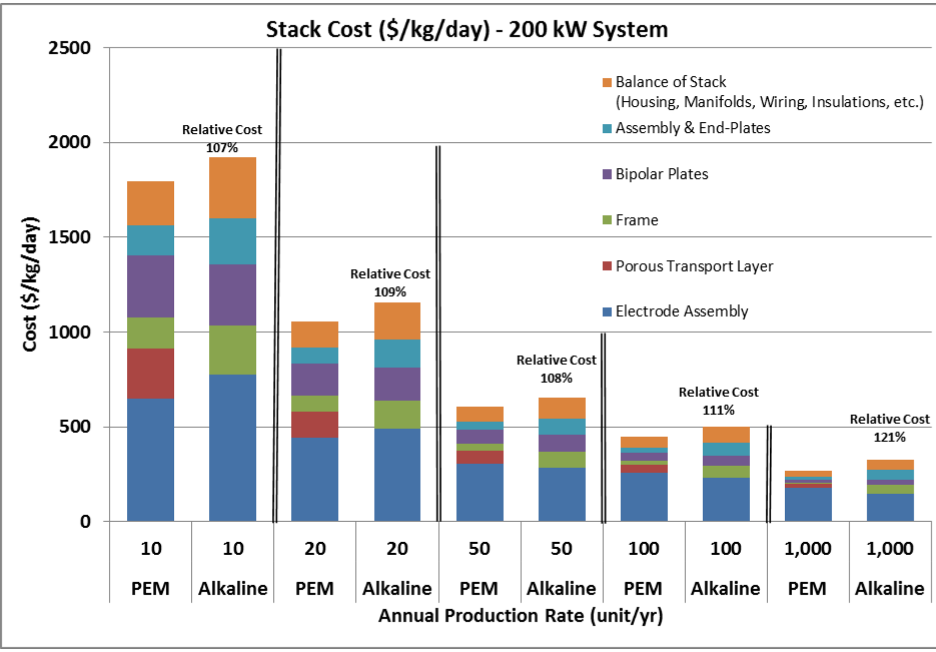
Comparative Cost Analysis (Stack Only)



Comparative Cost Analysis (Stack Only)



Alkaline vs. PEM Electrolyzer



- Alkaline electrolyzer stacks have larger cost in $/kg-$H_2$ basis and in $/kW basis