Liquid Alkaline Electrolysis Techno-Economic Review

Strategic Analysis Inc.
Presentation to:

US DOE "Experts Meeting on Advanced Liquid Alkaline Water Electrolysis"

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Outline

- Why TEA?
- Alkaline Design Evolution
- DFMA Design Basis
- Comparison of Systems (LA, PEM, AEM)
- Market projections
- Comparison of Cost Results
- Cost Reduction Opportunities

- LA = Liquid Alkaline
- PEM = Proton Exchange Membrane
- AEM = Anion Exchange Membrane

TEA Methodology

- Techno-Economic Analysis (TEA) is a tool to evaluate an entire system; evaluating the interactions between technical performance and cost.

Create System Model
-Process Flow Diagram
-Identify key process steps and variables

→

Conduct Mass/Energy Balance
-Identify product feed, and product output

→

Identify Key Processes and Key Equip. Info.
-Unit capacity volume production
-Process Equipment pricing

→

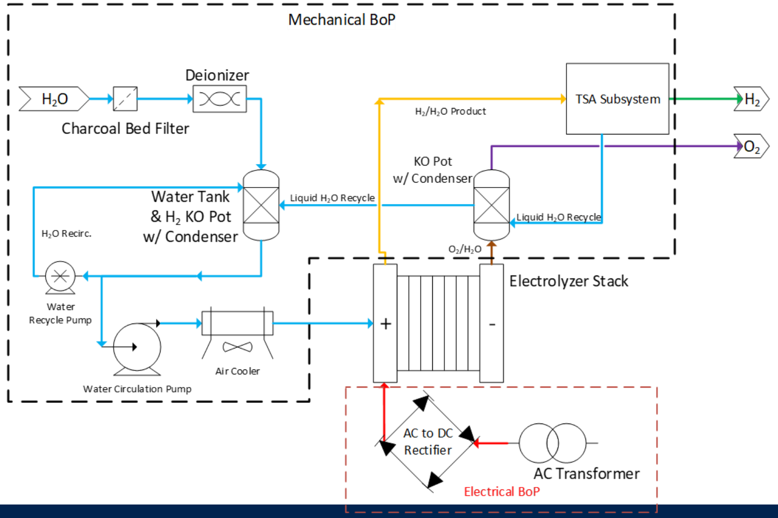
Estimate System Capital Cost
-Use DFMA®* to evaluate cost for materials, manufact., & labor for key components

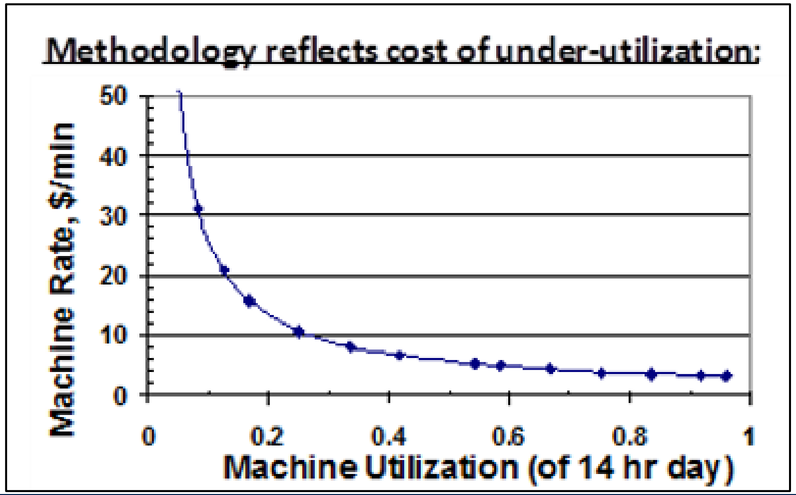
→

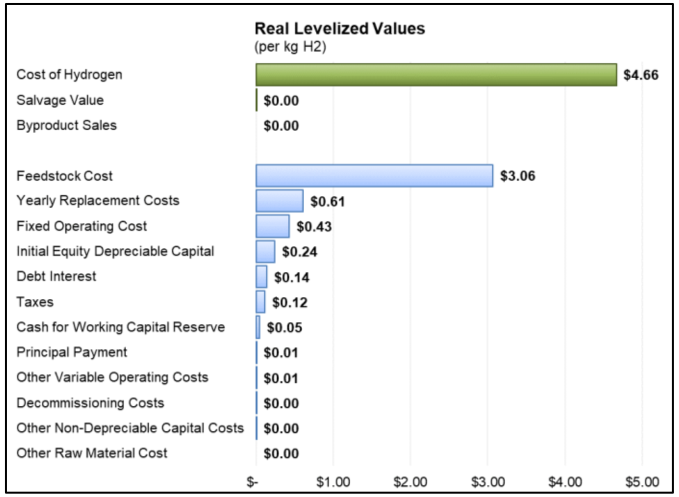
Evaluate Cost of H_2
-Input capital cost, operating cost, efficiency, etc. into H2 Analysis (H2A) tool

→

Post Analysis Process
-Review results
-Conduct sensitivity analysis





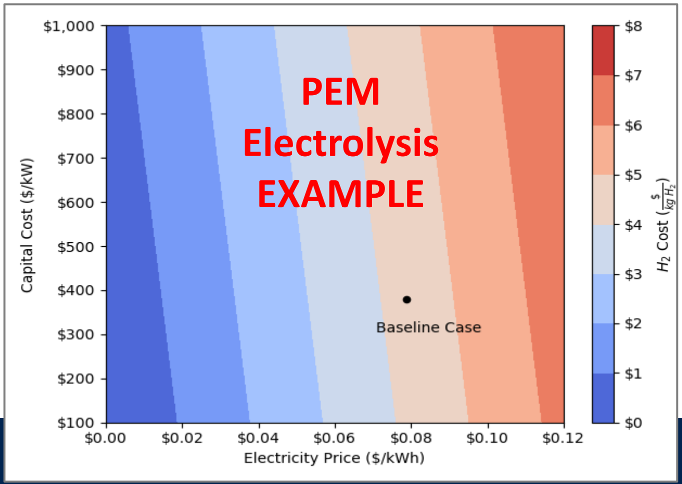


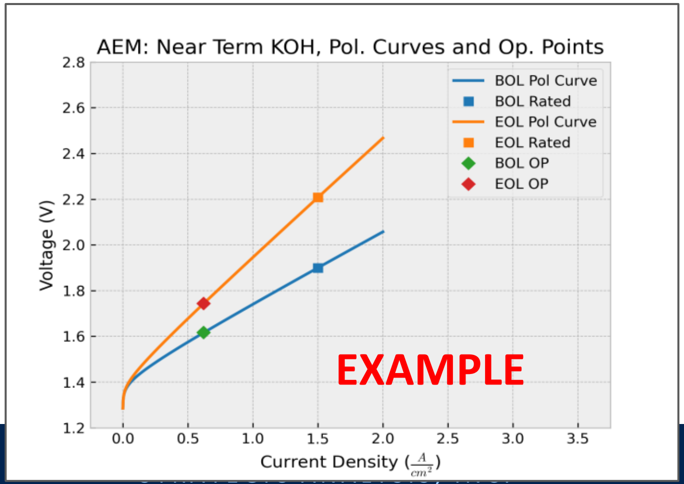
STRATEGIC ANALYSIS, INC.
*Design for Manufacture and Assembly (DFMA®)

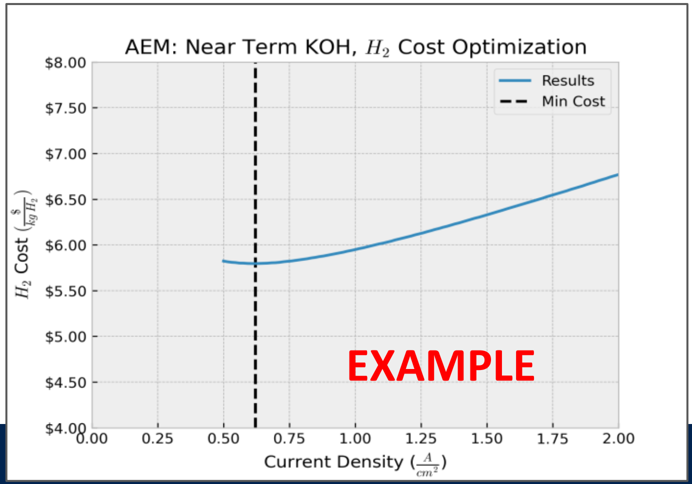
Opportunities for TEA

- Provide analysis that is **transparent, detailed, and made publicly available** to the technical community
- **Use Hydrogen Shot Target $1/kg to guide pathway technical targets**
  - Top-down approach of setting a cost target and determining the bounds of key performance or cost parameters that "must be" achieved
- **Incorporate performance and durability modeling to determine cost-optimal operating conditions and system configuration**
  - Example cases under investigation: Anion Exchange Membrane Electrolysis

1. Establish performance model with BOL and EOL operating curves based on degradation
2. Determine constant voltage (efficiency) vs constant current (production) operation
3. Determine most impactful parameters and establish interaction between H2A model and performance model
4. Run through range of specified operating conditions to determine lowest H2 cost







LA Configuration Overview

Finite Gap Vs. Zero Gap

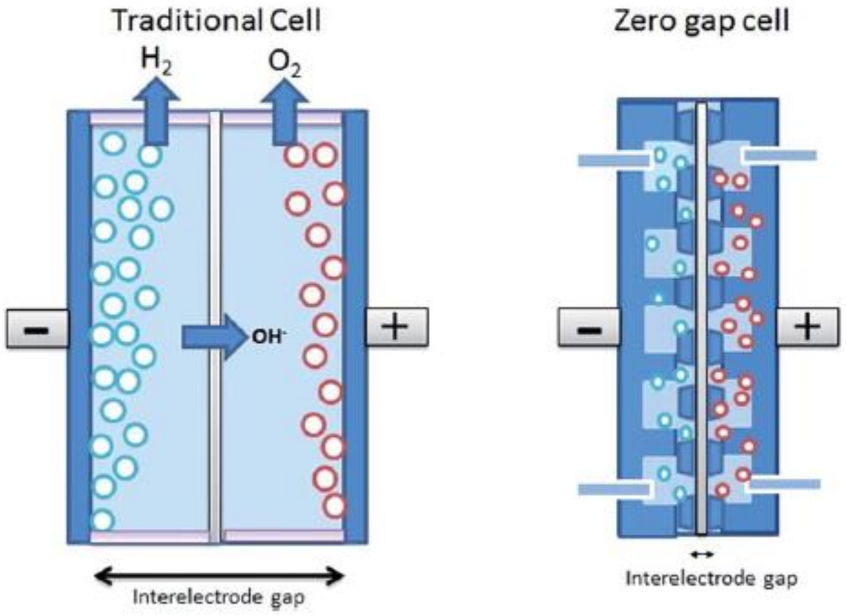
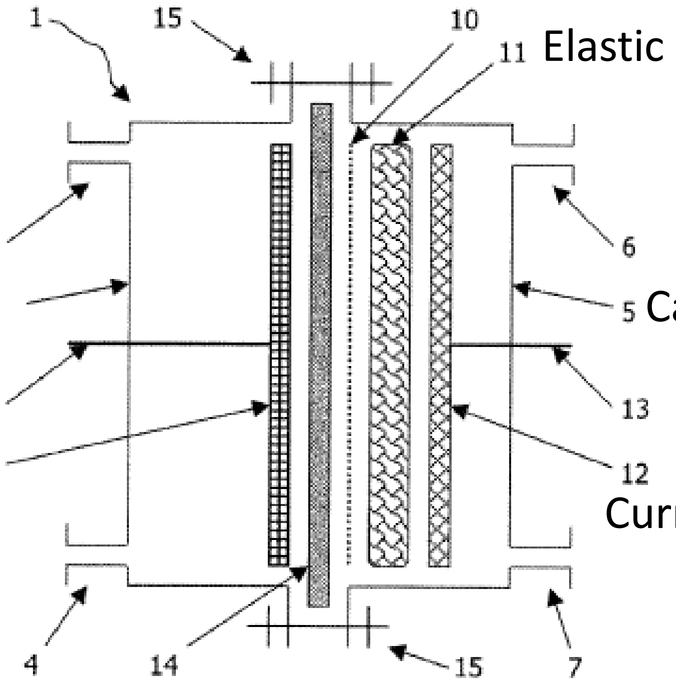


Fig. 4 Schematic showing reduction of inter-electrode gap from employing a zero gap cell design. This significantly reduces the overall cell resistance, increasing performance, particularly at high current densities. Note the loss in direct surface area between the pates due to the bubbles in the conventional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

Source: Phillips & Dunnill, 2016 [13]

Traditional/Old-Style LA had a 2-3mm gap between the electrodes and the diaphragm [12].
Modern Zero-Gap Designs press electrodes against the diaphragm.

Elastic Elements (for Zero Gap Design) to Press Electrode into Diaphragm



Source: [14] (2013 DeNora patent)

Expanded View of Elastic Elements

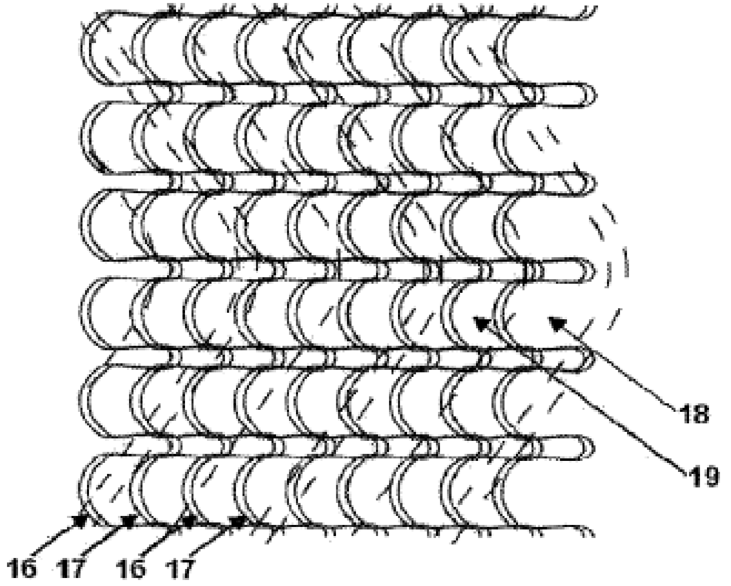
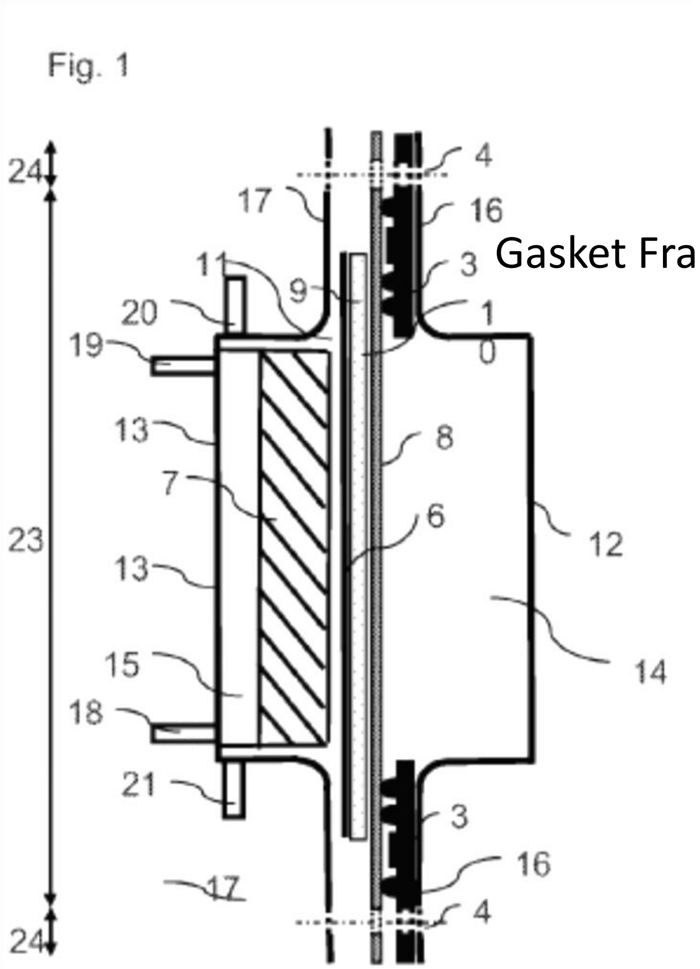


Fig. 2

Source: [14] (2013 DeNora patent)

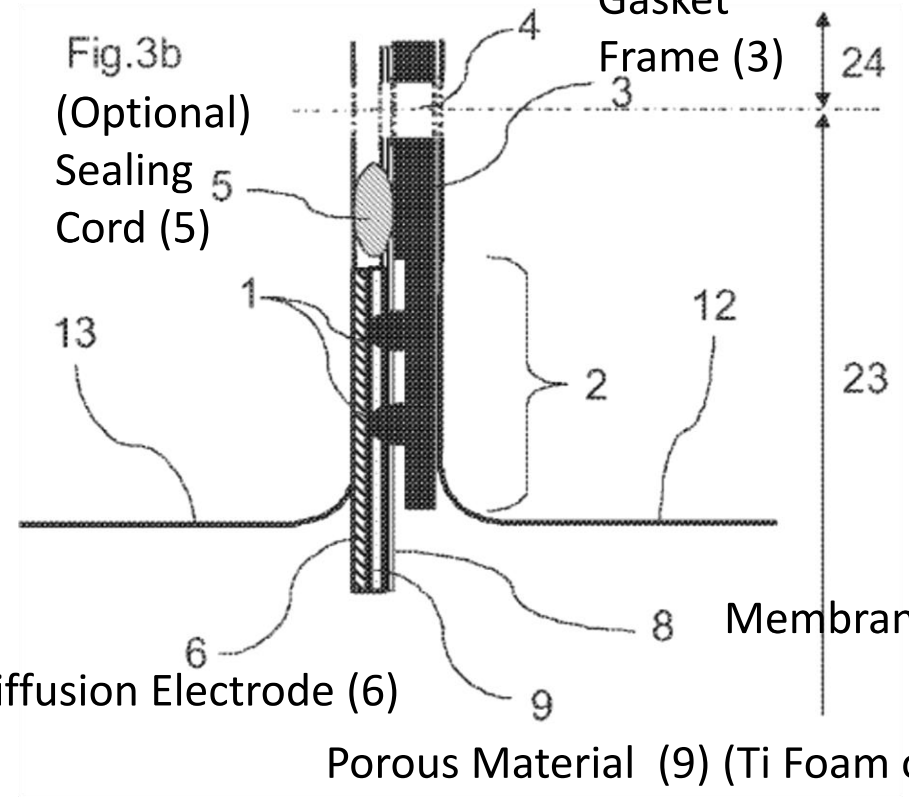
DeNora-Style electrodes (LA & Chlor-Alkali) use an Elastic Element to maintain a constant gap between electrodes. Traditional designs use a metal box/pan/flange to collect bubbles and route them away from the electrodes.

Frame Seal Elements to Seal Against the Porous Diaphragm



Source: [16] (2016 DeNora patent)

Explored view of Sealing Area



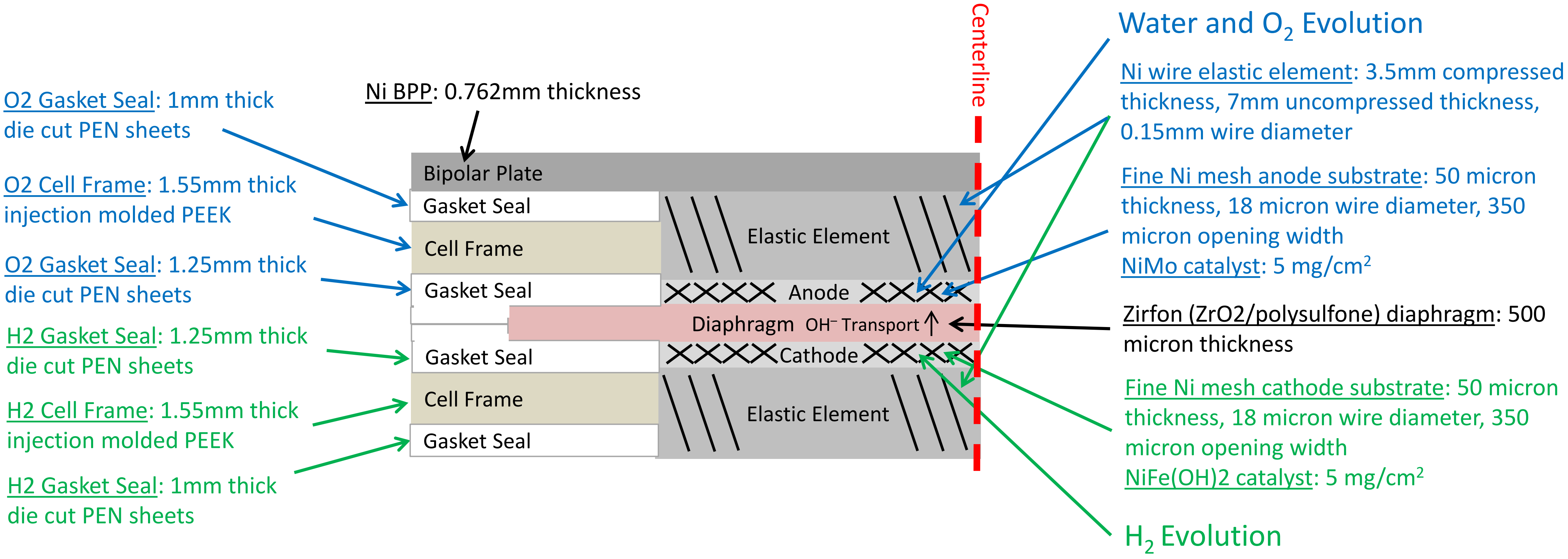
Source: [16] (2016 DeNora patent)

A Frame Gasket (with contours) can be used to seal the porous diaphragm.

SA Baseline Alkaline Cell Design

(SA-representation of traditional LA electrolysis cell)

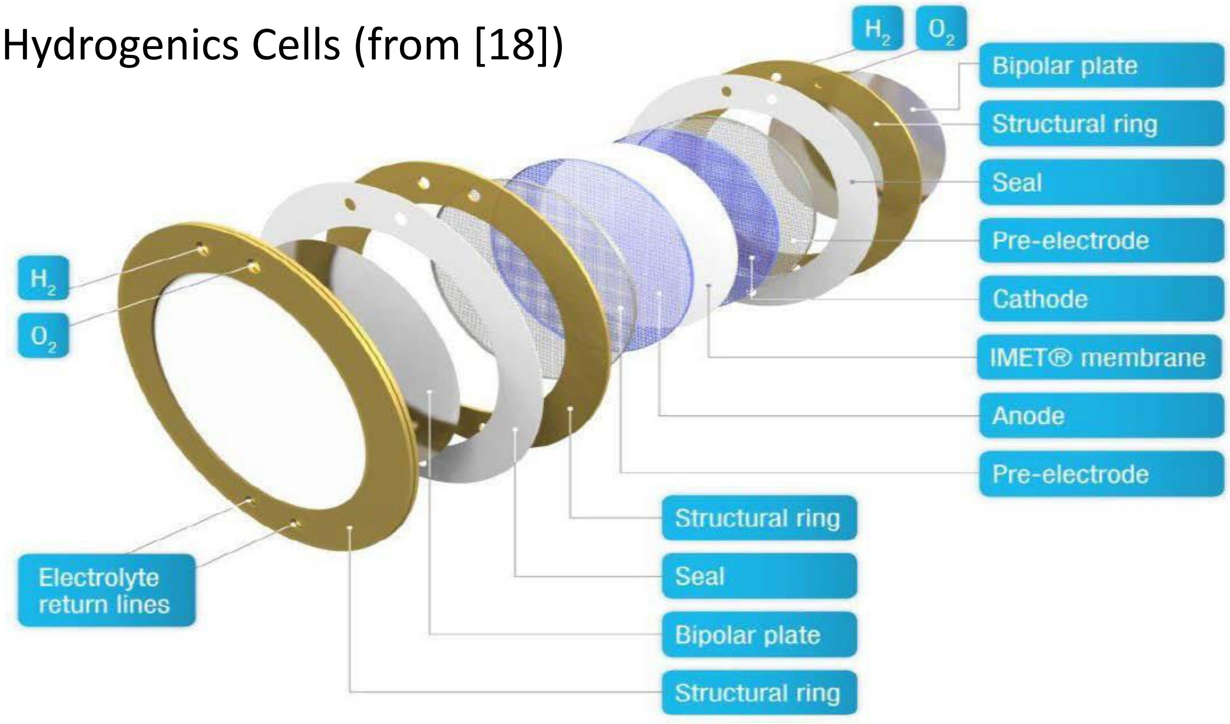
- Cross-sectional view of single Alkaline electrolysis cell
- Generic cell design: does not exactly match any one company (but is representative of key features)



SA design used for Baseline Cost Analysis.

NREL and Hydrogenics (~2017) Alkaline Design
(Both are simplified, PEM-like construction)

Hydrogenics Cells (from [18])



Layers of Repeat Cell:

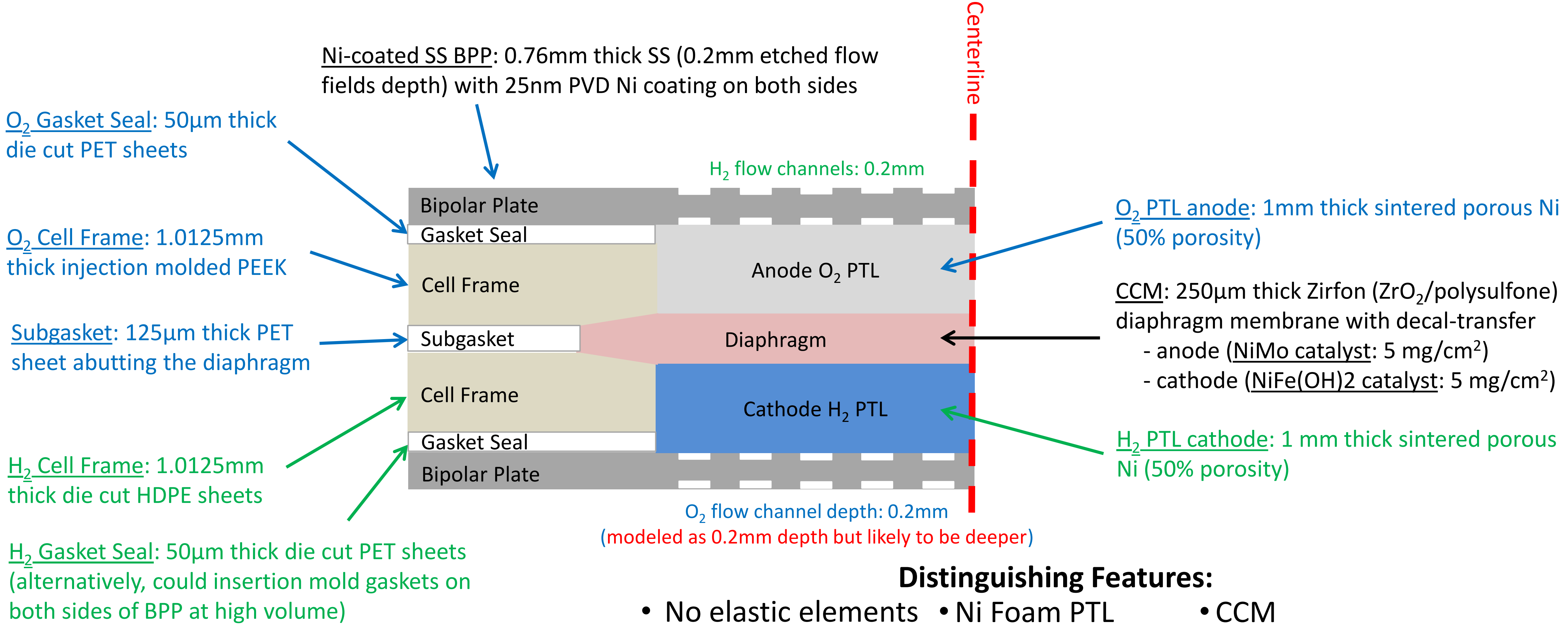
- Bipolar plate
- Seal
- Structural ring (cell frame)
- Seal
- Pre-electrode (Ni mesh or foam)
- Cathode (catalyst layer)
- IMET membrane (diaphragm)
- Anode (catalyst layer)
- Pre-electrode (Ni mesh or foam)
- Structural ring (cell frame)
- Seal

LA Electrolyzer Designs seem to be moving toward simplified, PEM-like fabrication:

- reduced part count
- easily assembled
- non-metal structural frames

SA Future Alkaline Cell Configuration

- Cross-sectional view of single ALK electrolysis cell
- Generic cell design: does not exactly match any one company (but is representative of key features)



Distinguishing Features:

- No elastic elements
- Ni-coated SS BPP
- Ni Foam PTL
- Simplified gaskets
- CCM
- Improved CD (1.2A/cm^2, 1.8V)

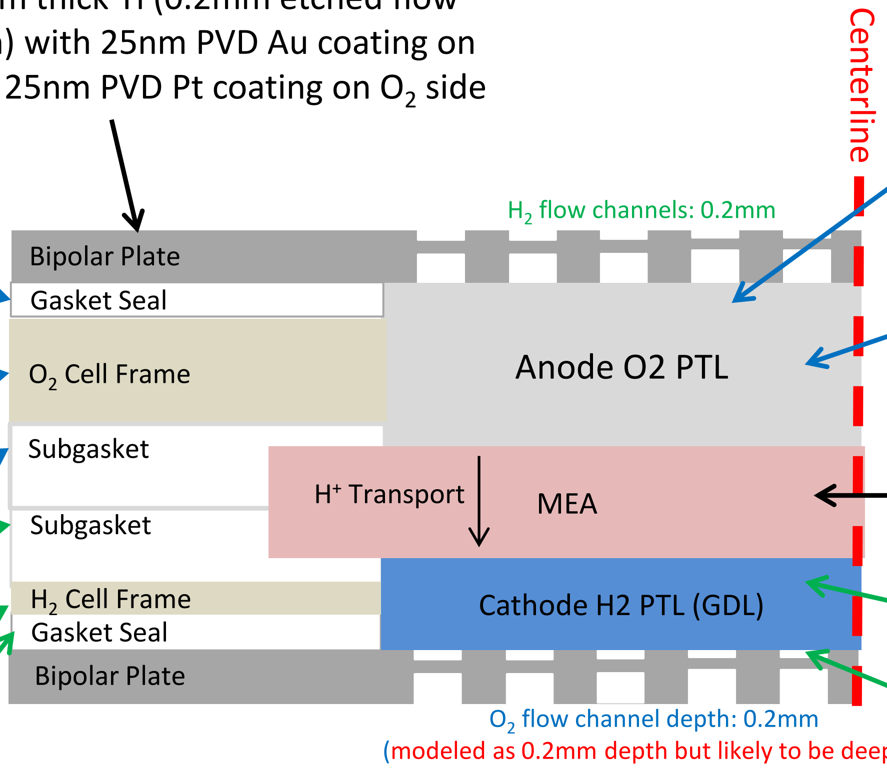
SA PEM Cell Configuration

- Cross-sectional view of single PEM electrolysis cell
- Generic cell design: does not exactly match any one company (but is representative of key features)

BPP: 0.76mm thick Ti (0.2mm etched flow fields depth) with 25nm PVD Au coating on H_2 side and 25nm PVD Pt coating on O_2 side

Water and O_2 Evolution

O_2 Gasket Seal: 50µm thick die cut PET sheets



O_2 PTL: Sintered porous Ti 1mm thick (50% porosity) with 100nm PVD Pt coating

O_2 Cell Frame: 925µm thick injection molded HDPE

CCM: 200µm thick ePTFE-supported PFSA membrane with slot die coated catalyst
O_2 side: 2mg Ir/cm^2 of IrO_2 on TiO_2
H_2 side: 1mg Pt/cm^2 at 30% Pt/C + 0.1mg Pt/cm^2 for GRC catalyst

Subgasket: 100µm thick PET sheets encasing membrane using 3M roll-to-roll process

H_2 GDL: 150µm thick (105µm carbon fiber substrate with 45µm thick MPL)

H_2 Cell Frame: 75µm thick die cut HDPE sheet

H_2 Evolution

H_2 Gasket Seal: 50µm thick die cut PET sheets (alternatively, could insertion mold gaskets on both sides of BPP at high volume)

Liquid Alkaline Electrolysis Alternatives & Advanced Features

Diaphragm
- Thinner diaphragm thickness
- Alternative to Zirfon Perl UTP 500 (polysulphone with ZrOx)
  - IMET
  - PBI: m-PBI [18], ion-solvating/ KOH-doped PBI [8]

Elastic Elements
- Eliminate entirely
- Use only on one electrode [21]
- Alternate materials
- Alternate coiling/construction

Frames
- Alternate metals
- Resins (vinyl chloride, PE, PP, PPS, PSF, Epoxy, etc.) [14]
- Injection Moldable: PPS-40GF, PEEK [18]

Seals
- Teflon, EPDM, PEN

PTL/Current Distributors
- Ni Foam, Ni Mesh
- Expanded metal (Thyssenkrupp Chlor-A) [5]
- Plastic mesh (coated) [20]

Catalysts
- Baseline: Ni-Mo and Ni-Fe$(OH)_2$
- Pt/Ru/Rare-Earths [1], RuO2 [29]
- No noble metals
- No catalyst on anode/OER side [1]

Electrodes (Supports)
- Eliminate via applic. directly to membrane (CCM) or PTL
- Alternatives to fine woven Ni mesh
  - Foams [7]
    - Possibly with graded porosity [13]
  - Microfibrous felts [7]
  - Nanowire felts [7]
  - Ni-coated steel [11]
  - Porous carbon paper [13]
  - Catalyst coated Perforated Ni sheet [13]

Bipolar-Plate/Separate-Plate
- Ti, Ni, SS/Mild-Steel with Ni coating [30]
- Flow fields or no flow fields

Other Ideas
- Plastic Stack (use of plastic-framed cartridges, melt-welded to form a sealed stack [20]

Asahi Kasei Illustration of an Advanced LA Cell

Source: [30] (Asahi Kasei 2009)

(For Chlor-Akali operation)

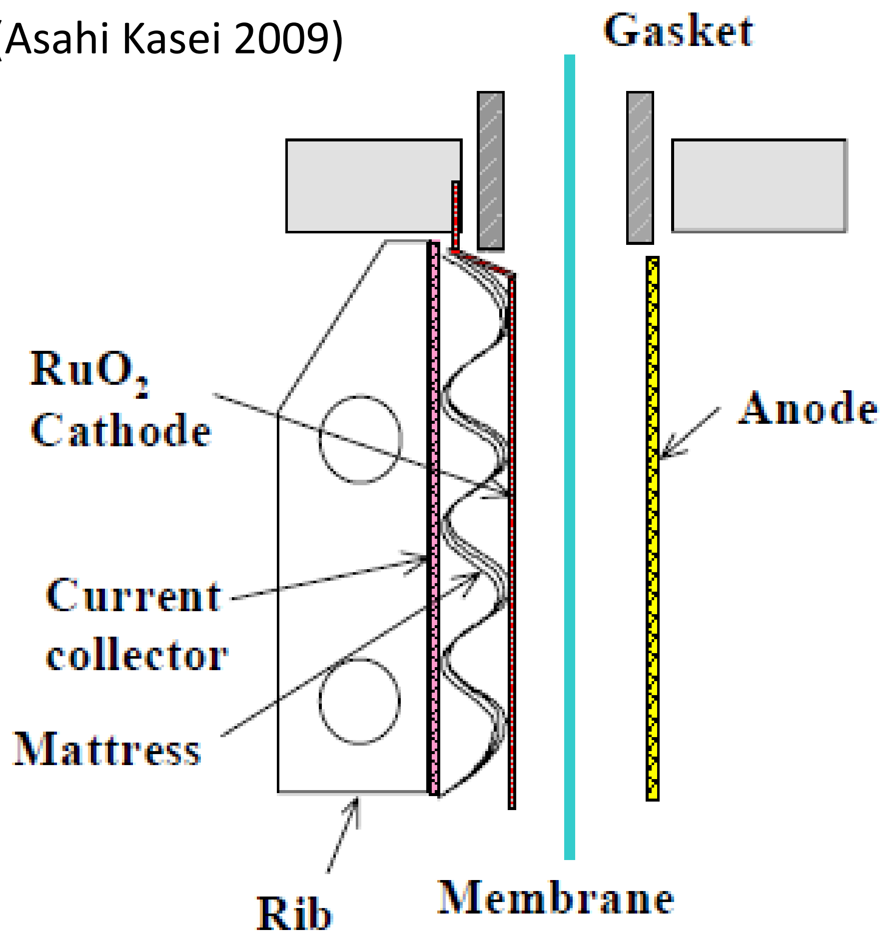


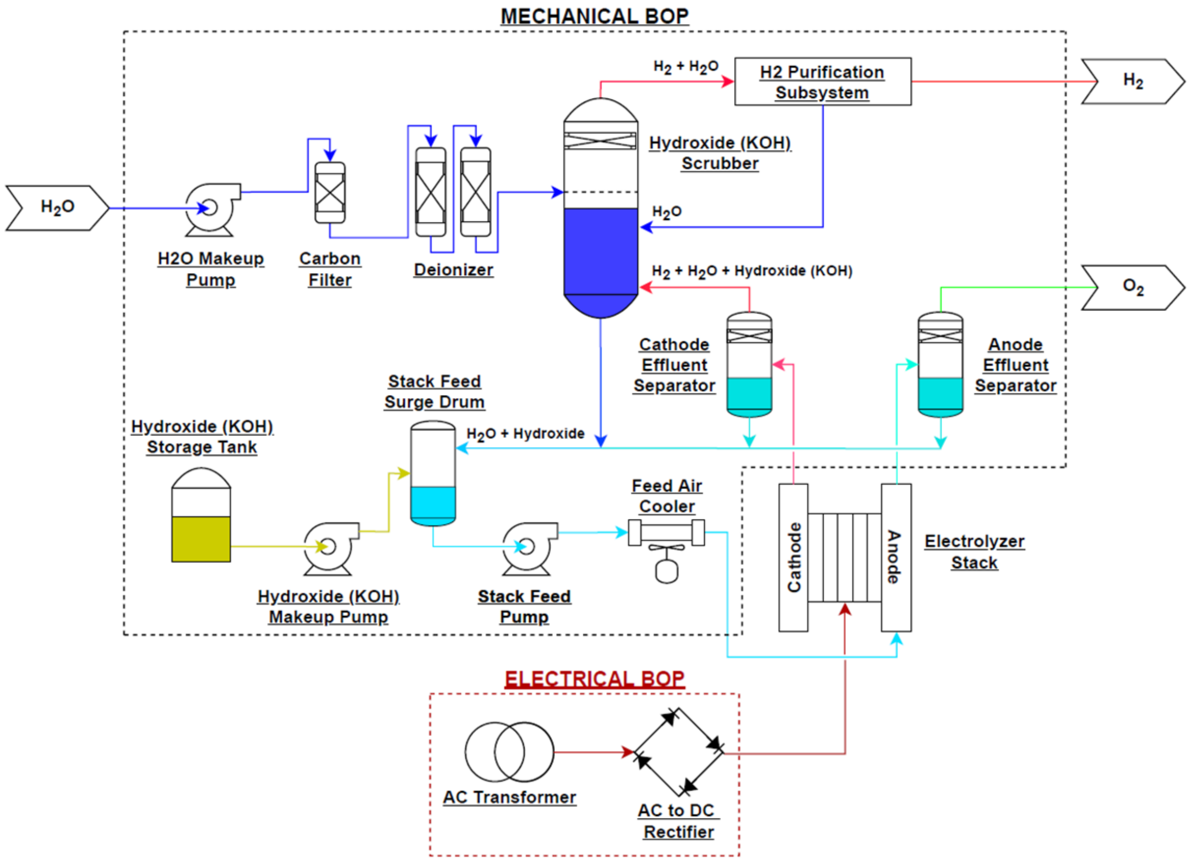
Figure 8. Cross section structural view of AKCC zero gap cell.

Illustrates:

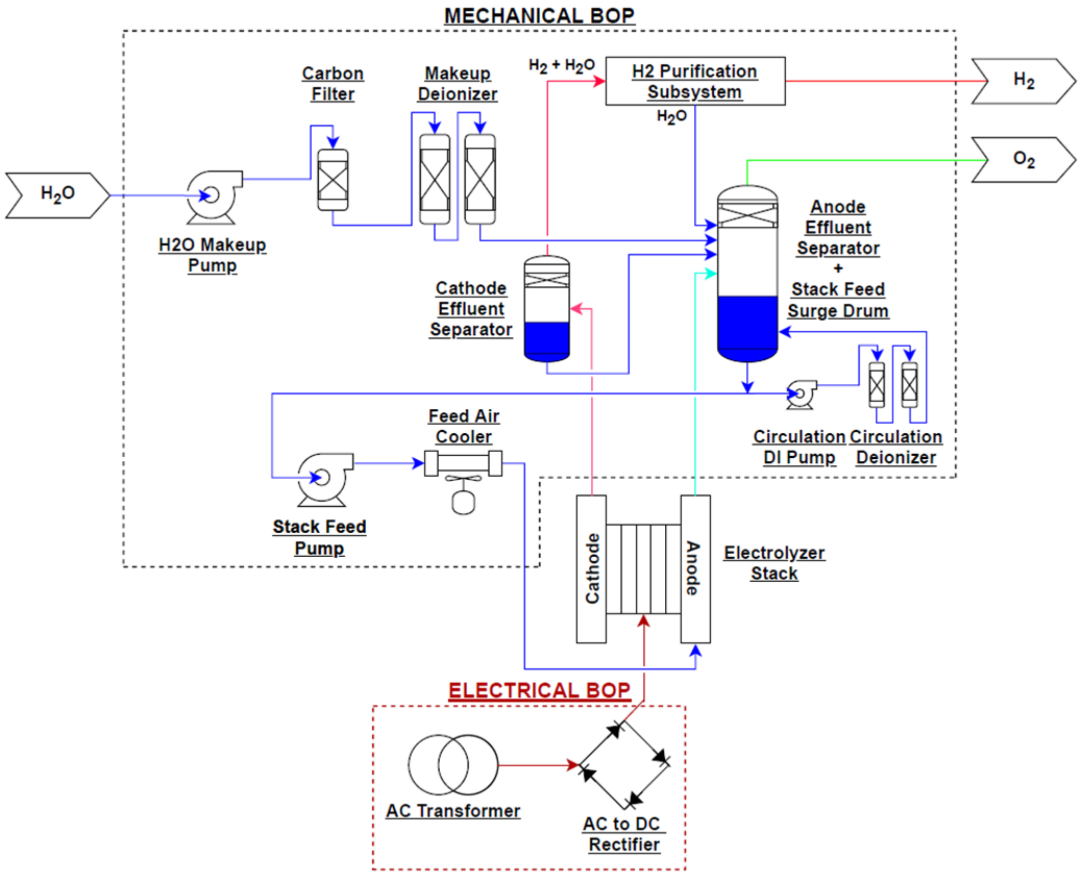
- Zero-Gap cell
- Advanced catalyst (RuO_2 cathode)
  - Applied via thermal decomposition
- Fine Ni mesh electrode substrate
- "Mattress" Elastic Element (on only one side)
- Current Collector
- Cell Frame
- Gaskets against membrane

System Diagrams

LA Electrolysis System



PEM Electrolysis System



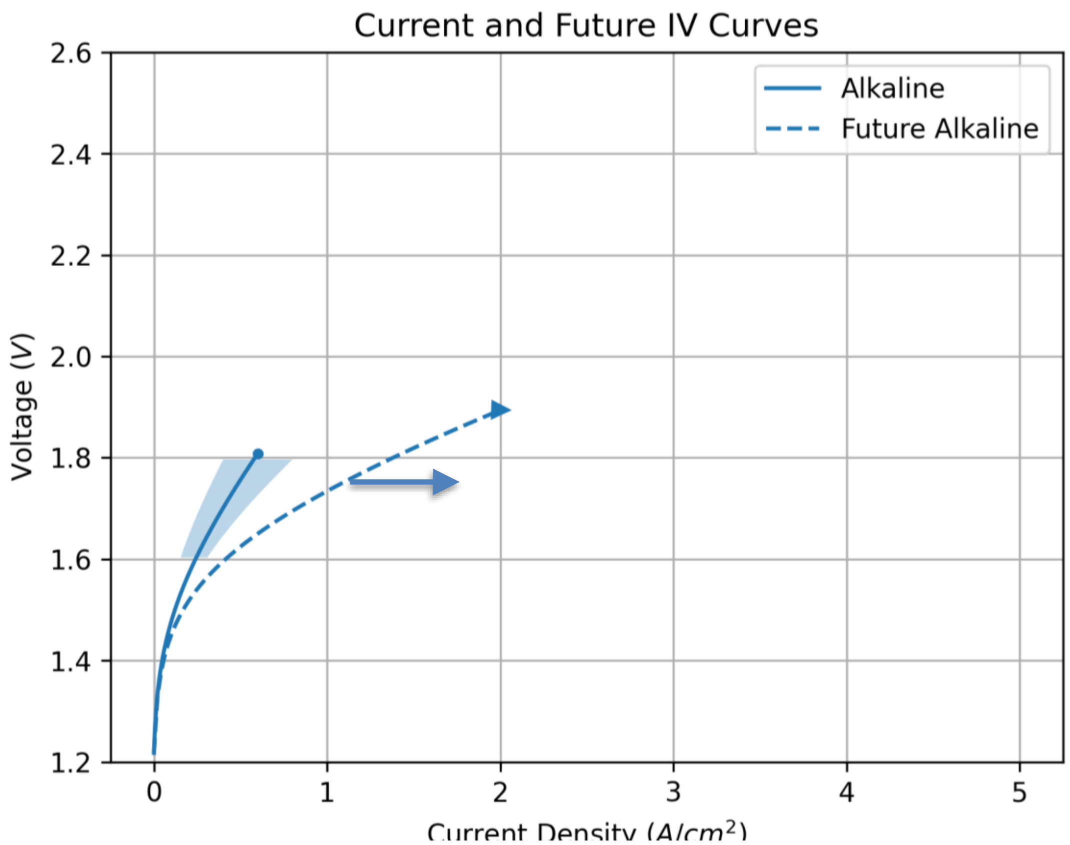
Advantages & Disadvantages of Electrolysis Technologies

Technology	Pros	Cons
Liquid Alkaline	• Stronger current market position • **Lowest CAPEX, ~equal OPEX, longest lifetime** • Mature technology with expanding manuf. base • No obvious supply chain concerns	• Perceived limited technical improvement (maturity) • Limited dynamic operation (~s), slow start-up (~0.5 h) • Lower product purity • KOH handling
PEM	• Excellent operating characteristics: dynamic response ~ms, <5 min SU • **Higher product purity and *(theoretically)* pressure** • Expected technical advances • Lower system footprint • Pure water system/No KOH	• Higher CAPEX, no **clear** OPEX advantage • Precious metal costs & supply chain concerns • Shorter lifetime than ALK
AEM	• **Expected lower catalyst and membrane cost** • Use of SS (instead of Nickel) • Low/No use of KOH (improved handling, materials compatibility, safety)	• Lifetime/membrane durability • Low current density (both on pure water and in 1M KOH)

LA response is "slow" compared to PEM. But is it fast enough for Renewable (with hybridization)?

AEM research focus is on pure-water operation. But KOH improvement in CD and lifetime may be worth it.

Current and 2030 Polarization Curves



Most customers are agnostic about *how* H_2 is produced: care about **price, pressure, purity, and footprint**

Operating point selected for each system independently and depends on application conditions

- Hydrogen refueling station using grid energy might choose low voltage *(high electrical efficiency)* while a solar-associated system might select high current density *(low capital cost)*
- The entire system is designed around the expected conditions and operating point: can lead to orthogonal development directions
- Current “standard” operating points:
    - Alkaline: 0.4 – 0.8 A/cm^2, 1.9 – 2 V/cell

**Shaded areas show expected operating ranges*

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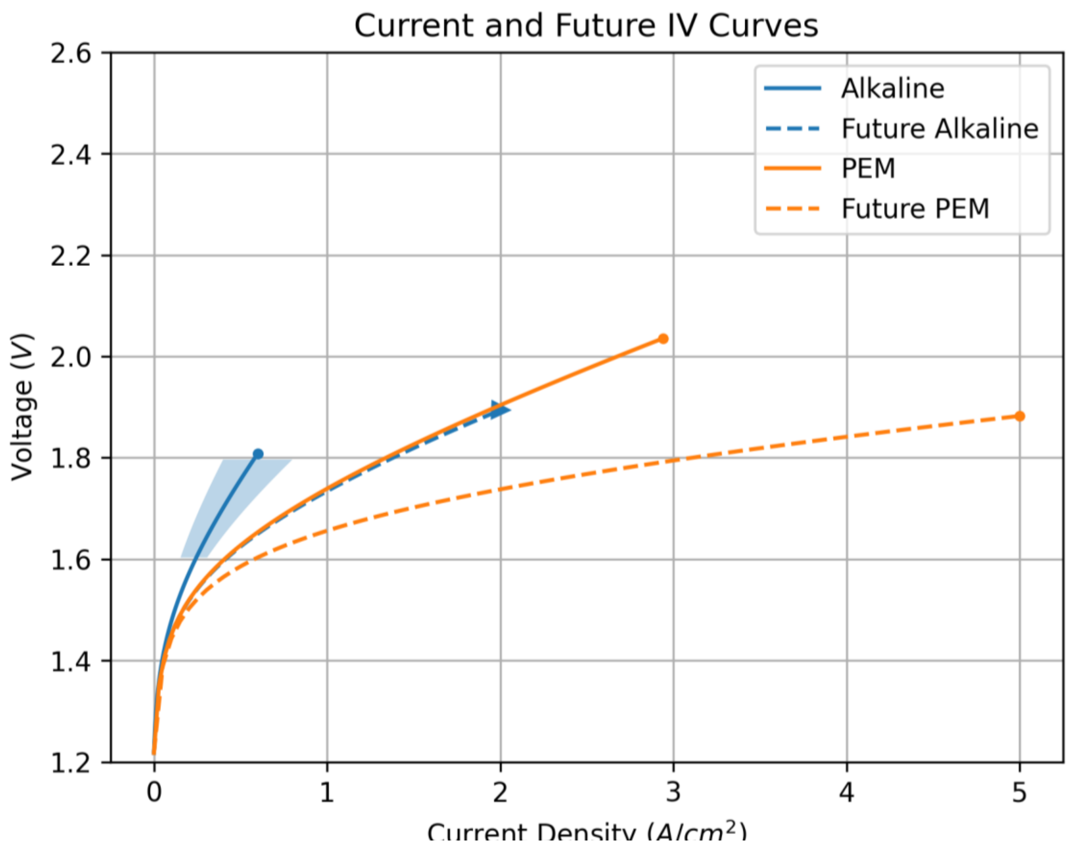

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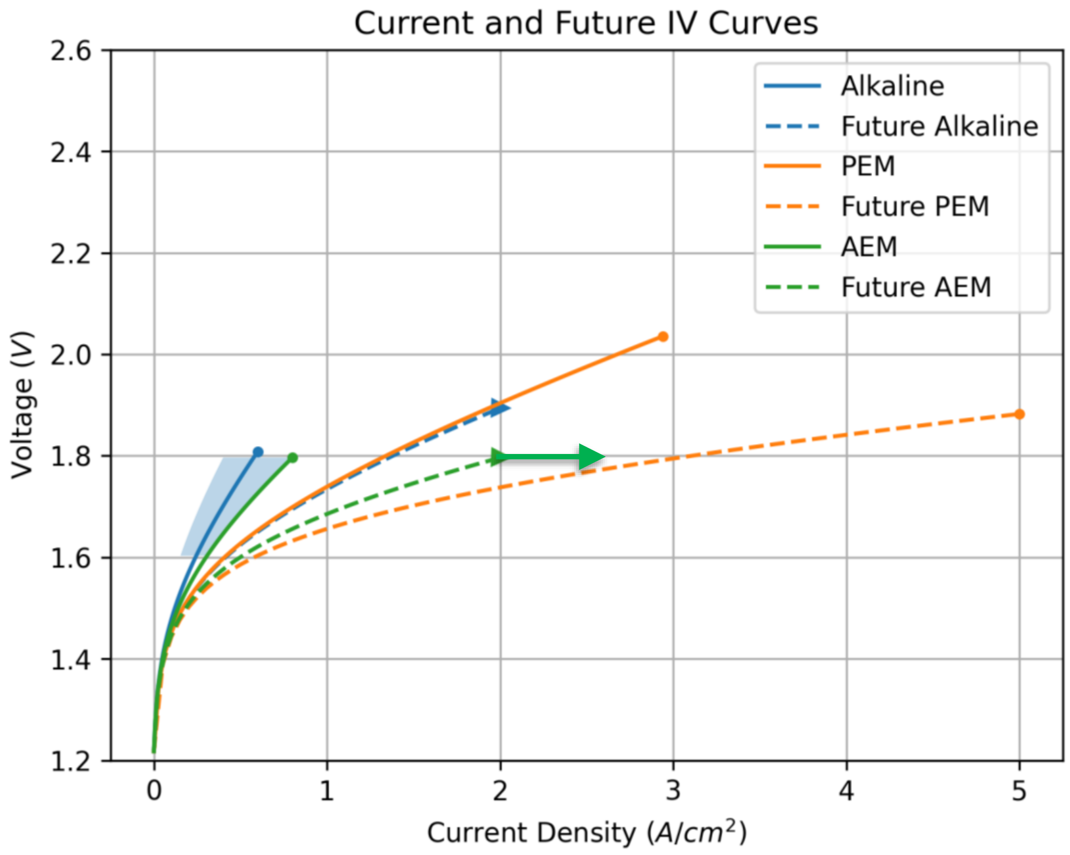

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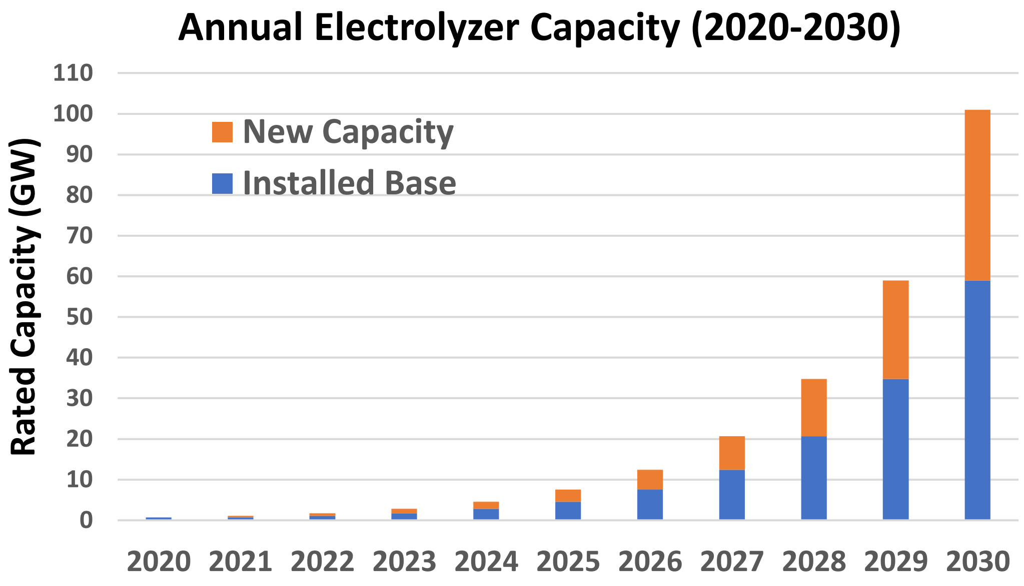
  - Alkaline: 0.4 – 0.8 A/cm^2, 1.9 – 2 V/cell
  - PEM: 2 – 2.5 A/cm^2, 1.9 – 2 V/cell
  - AEM: ~0.4 – 0.5 A/cm^2, 1.8 – 2 V

**Shaded areas show expected operating ranges*

Electrolyzer Market Outlook

- Future growth largely driven by EU: combination of government policy & investment money and firm decarbonization pledges
- Manufacturing base expanding rapidly: multiple gigawatt/year-scale factories in development
  - ITM: 0.35/1/2 GW, PEM, ThyssenKrupp: 5GW, LA, NEL: 0.5/2GW, LA, PlugPower/IGW: ~1GW, PEM, McPhy: 1GW, LA, Enapter: ~5GW, AEM
- Majority of electrolyzer projects paired with renewable electricity generation: wind, solar, hydro



Strategic Analysis Internal Projection based on compilation of public data

PEM vs. Alkaline?

Framework 1:

- LA is currently much less expensive and produced in higher quantities
- Maintains its cost lead over PEM and is the dominant technology in 2030 and beyond

Framework 2:

- PEM has more technology-improvement potential
- Superior dynamic response allows PEM to captures most/all of electrolysis market linked to renewable energy
- Scaling reduces costs to lower/equal to LA
- PEM captures equal or greater total market share in 2030 and beyond

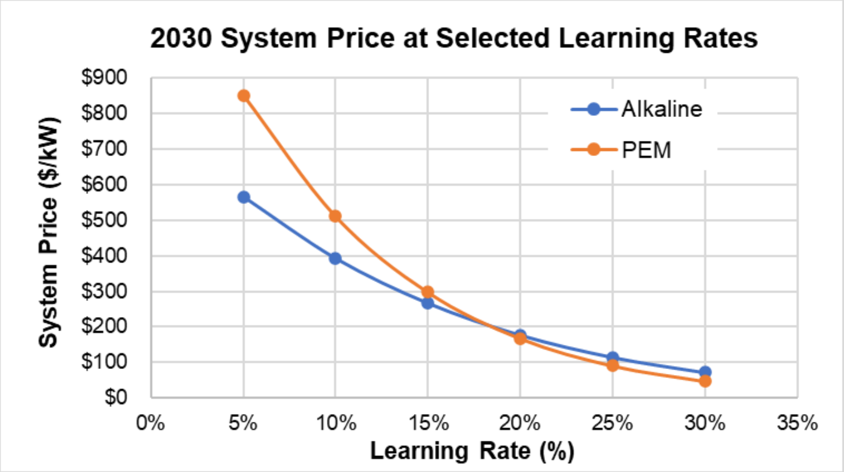
Learning Curve Approach Suggests <$500/kW System Prices for Both LA and PEM

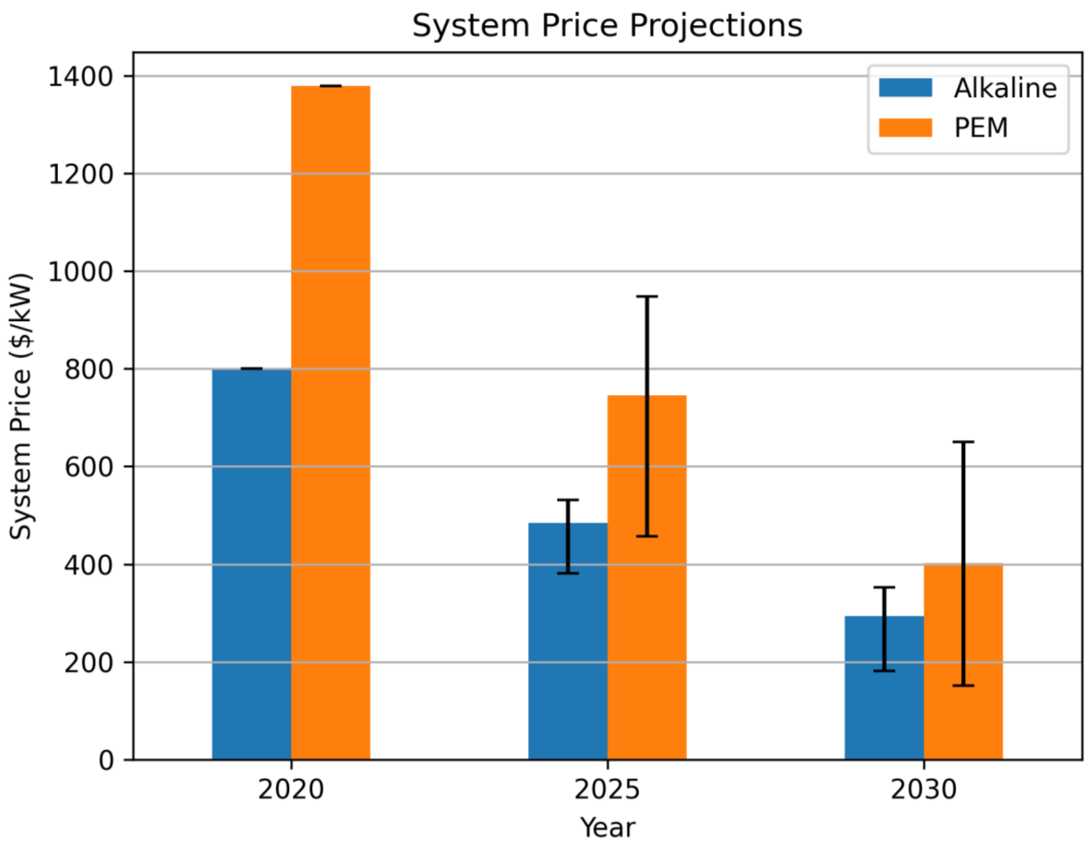
- Renewable energy learning rate estimates:
  - Wind Energy: 19% (BloombergNEF)
  - Solar PV Modules: 24% (BloombergNEF)
  - Lithium-ion battery packs: 20% (Ziegler & Trancik, 2020)
  - Bloom SOFC: 28% (company presentation)
  - Plug Power PEM: 25% (2019 company presentation)

Learning rate cost estimate model inputs:

Technology	Cumulative MW to date*(est.)	Cumulative 2030 MW (est.)	2020 Costs ($/kW)
Alkaline	600*	60,000	$800
PEM	50	40,000	$1,380

*included pre-1975 alkaline systems at a 50% discount

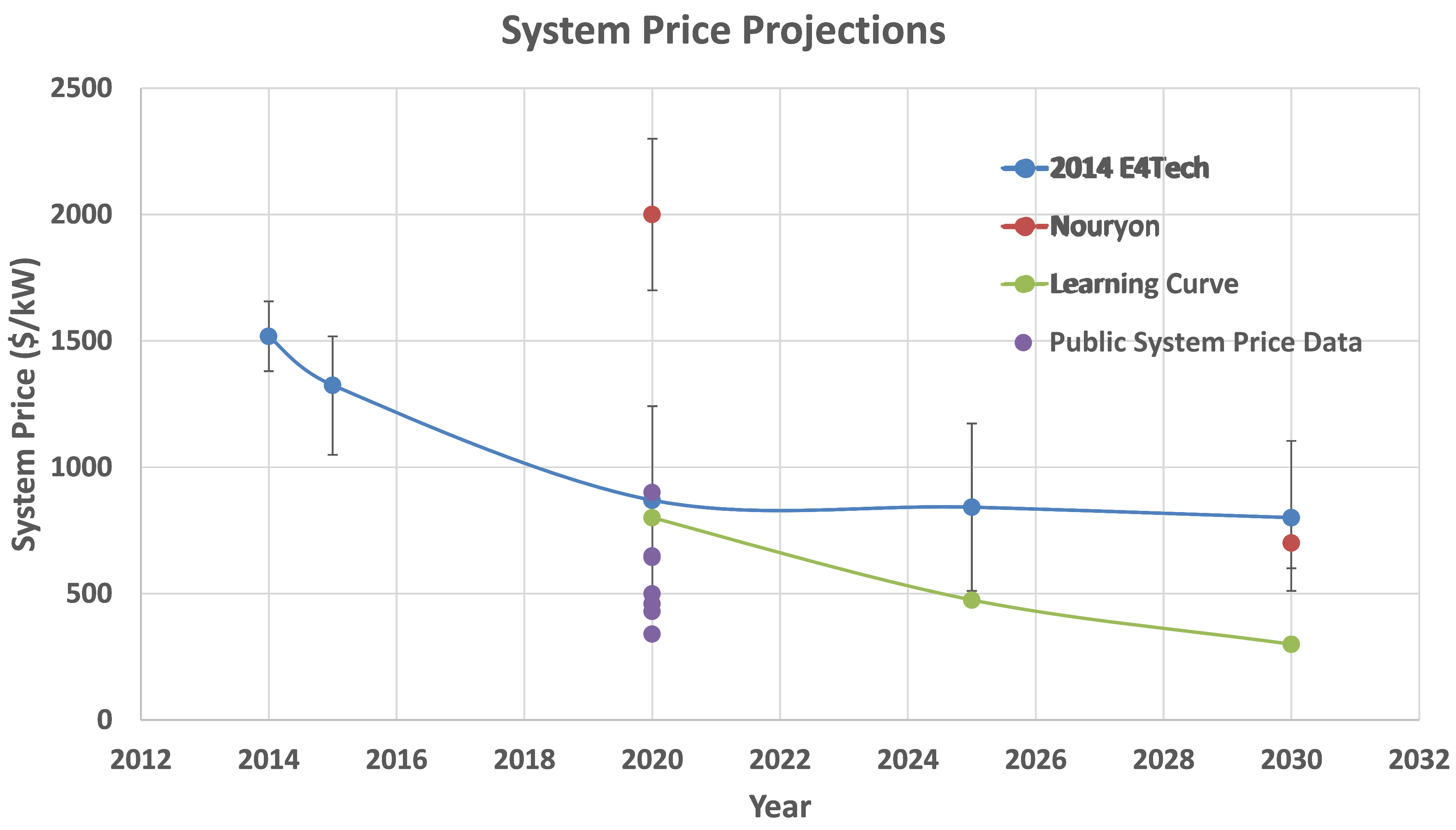




Estimates shown combine learning rate assumptions with manufacturer & expert price projections (Not based on DFMA)

PEM and Alkaline electrolyzer price near-parity is expected in 10-15 years.

System Price Projections from Variety of Sources



- **These are Prices, not Costs**
- **Trend-line is downward**
- **Lowest priced ~2020 systems tend to be Chinese**
- **Full details & assumptions are not known. (That's why we are doing a full DFMA-style analysis)**

Nouryon Projects Future LA Electrolysis to be <$100/kW Stack and <$1000/kW System

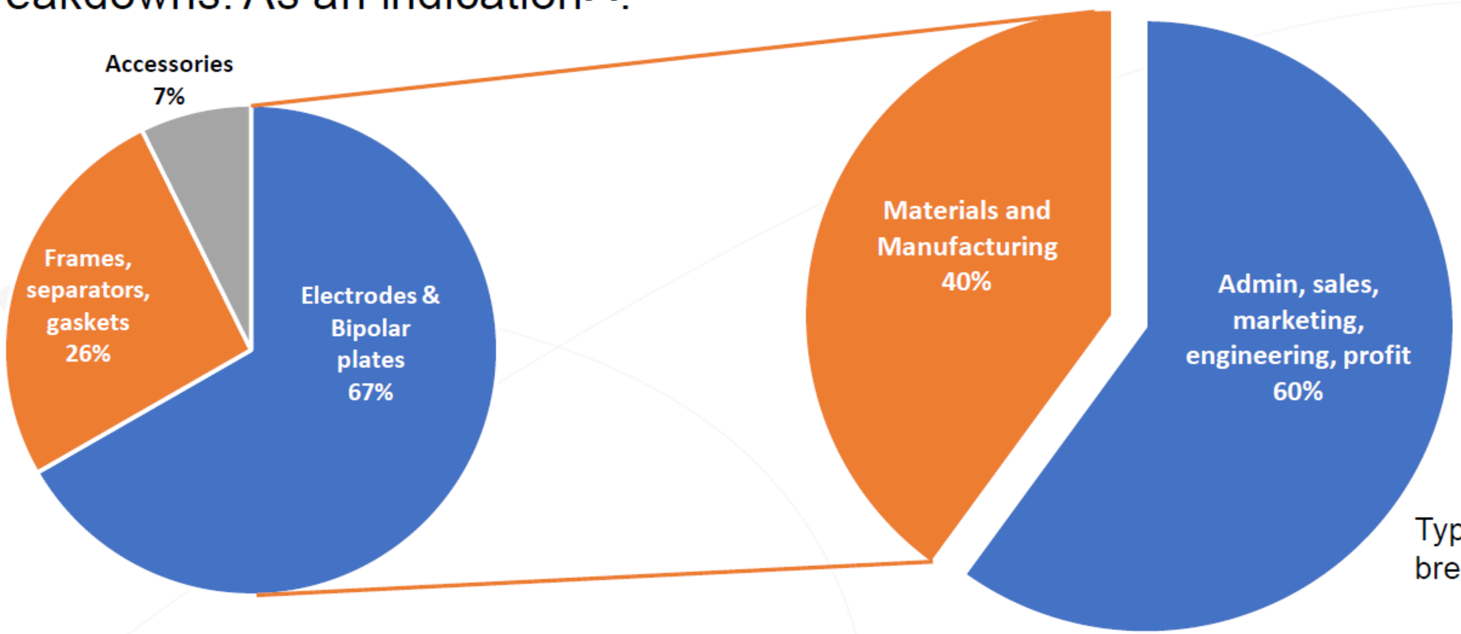
Nouryon, formerly AzkoNobel, is a Dutch multinational specialty chemical company

Nouryon

Cost breakdown

Different stack designs have different cost breakdowns. As an indication[1]:

Materials and manufacturing contribute significantly to the stack cost:



Typical product cost breakdown[2]

[1] FCHJU Report: Study on development of water electrolysis in the EU (2014)
[2] PLTW, Introduction to manufacturing processes

Electrochemical Conversion & Materials conference - June 2019

2019 Nouryon Projections

Current Costs:

Stack	$115 - $700/kW
BOP	$230 - $460/kW
Other	$1,150/kW
Total	$1,700 – $2,300/kW

Future Targets:

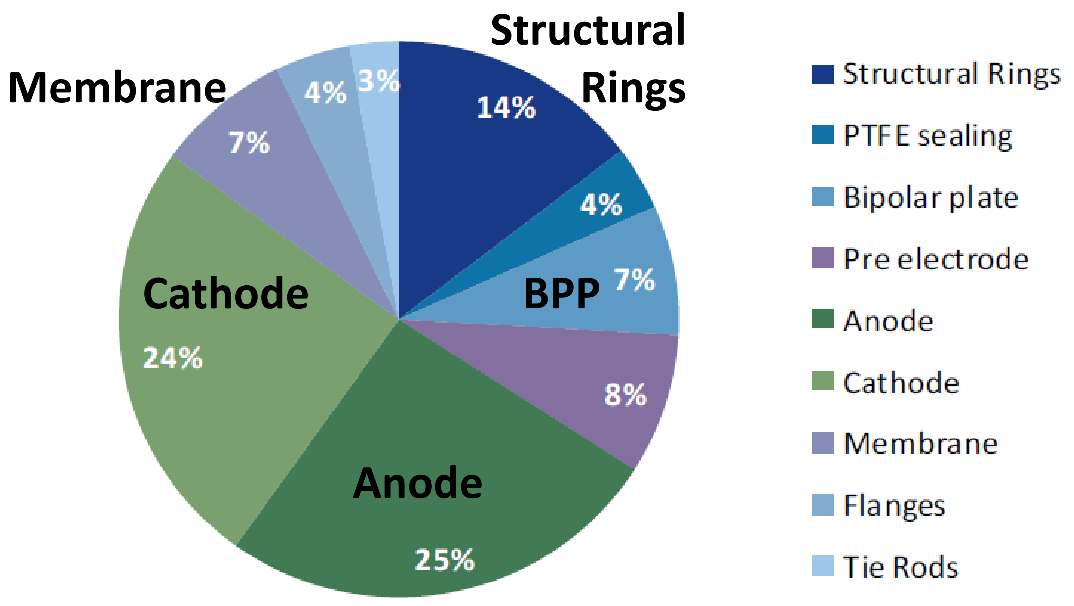
Stack	$<115/kW	
BOP	minimize	~$500 to 700/kW
Other	minimize	
Total	~$600-$800/kW	

Source: [30] (Nouryon 2019)

Electrolyzer Stack Cost Breakdown
(from 2014 E4tech Report to FCHJU [32])

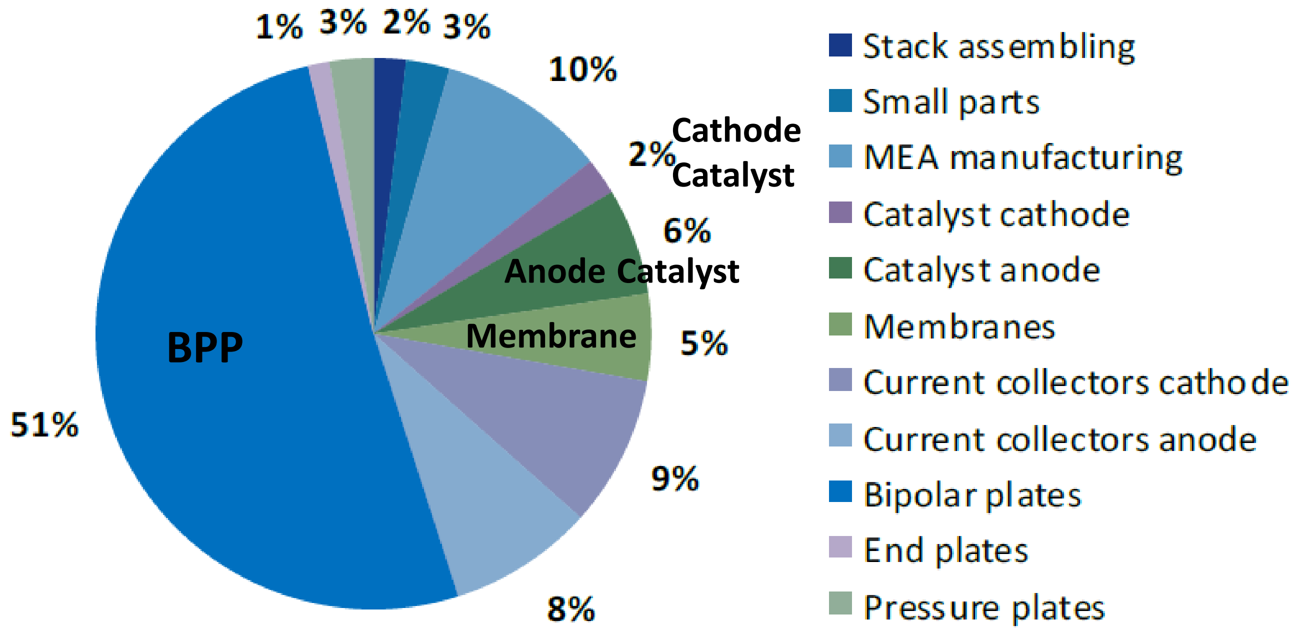
Cost "breakdowns shown are very generic, as system designs are manufacturer-specific"

Liquid Alkaline



(E4tech based on various sources)

PEM



(E4tech based on various sources)

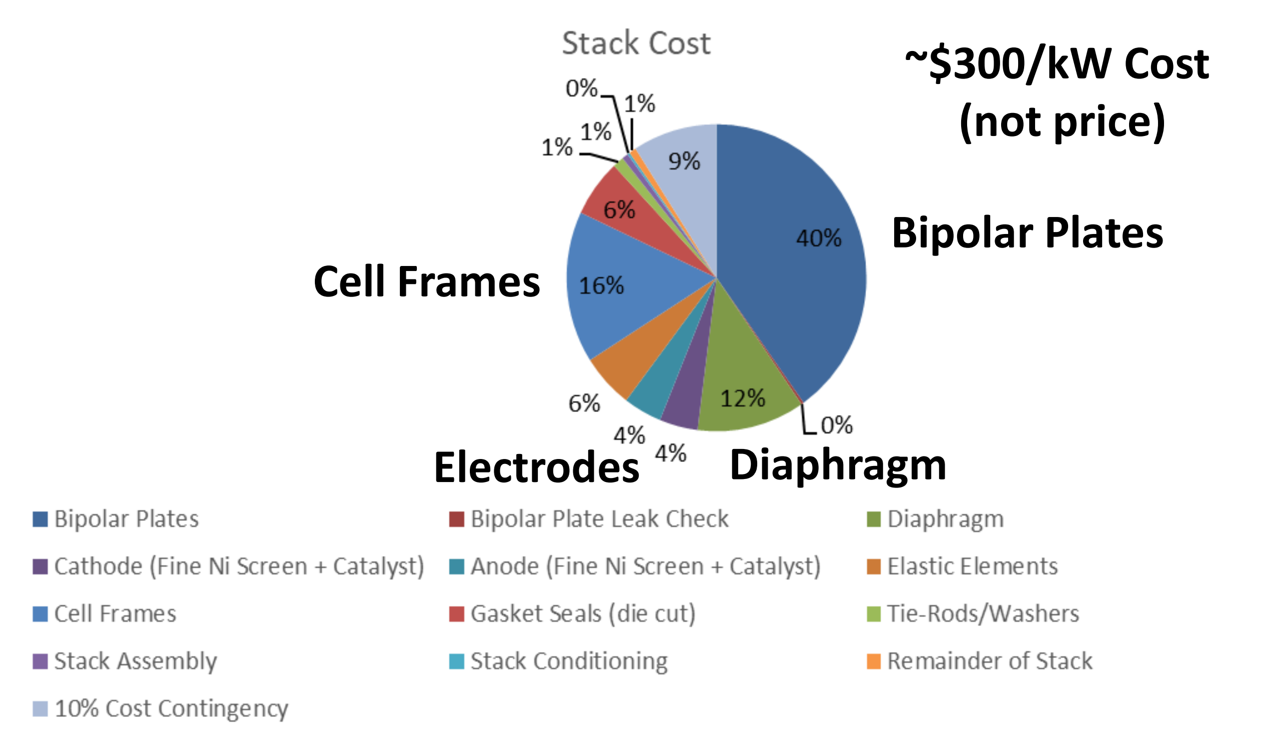
Electrodes & BPP ~56%
(broadly consistent with Nouryon projection of 67%)

PEM Bipolar Plate cost ~50% of stack cost.
Note: Anode/OER catalyst cost is modest but the analysis pre-dates recent 10x spike in Iridium price

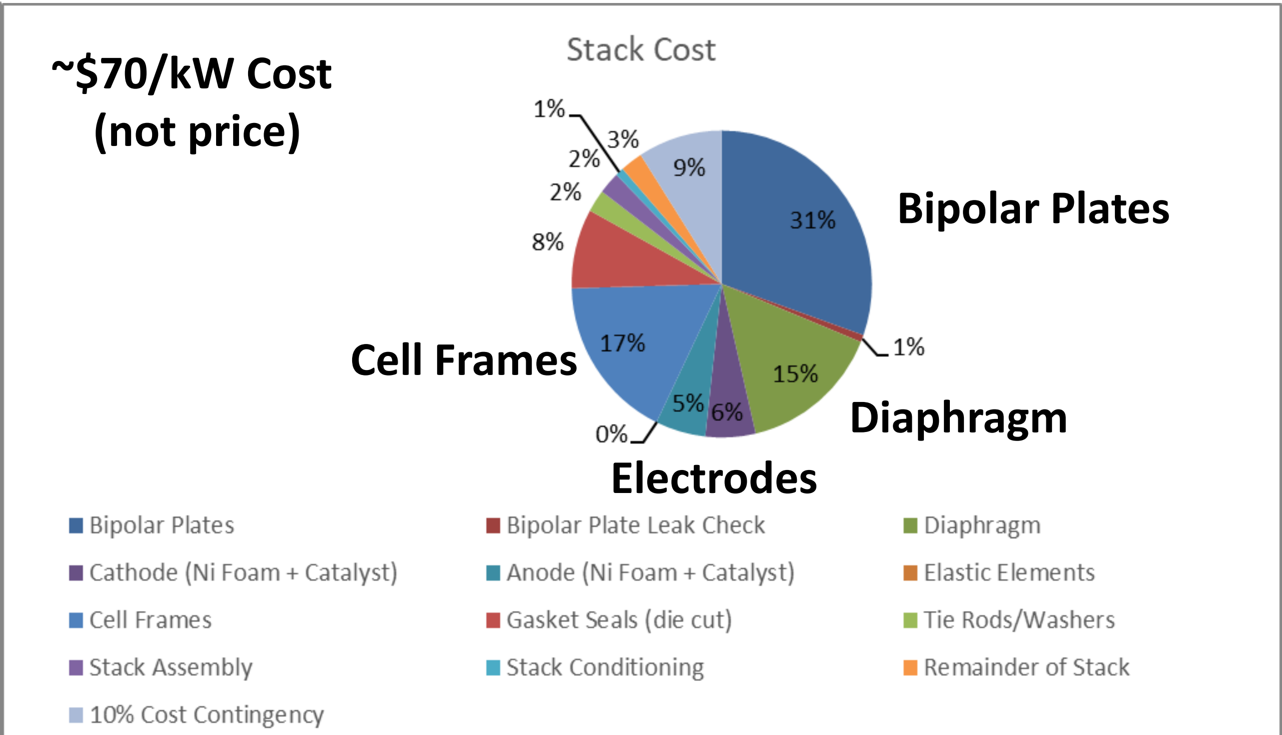
LA Electrolyzer Stack DFMA

Preliminary Results: DFMA Analysis in Progress

Baseline: 5MW Stack (500 MW/year)



Future/Advanced: 5MW Stack (500 MW/year)



Both Stacks: 1m² active area
Baseline: 0.4 A/cm² at 1.8 V/cell
Future: 1.0 A/cm² at 1.8 V/cell

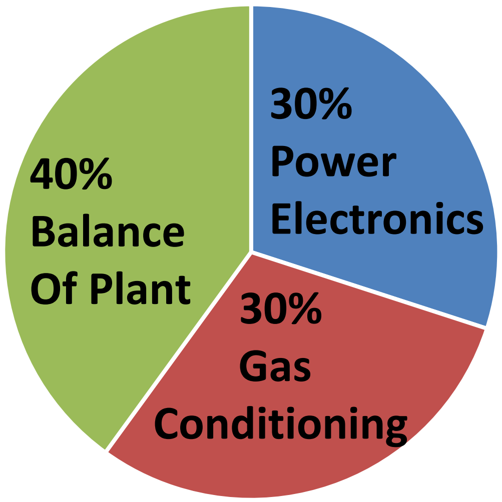
Trends:

- **Large cells and large stack powers are cost-favored**
- **Simplified cell design reduces cost**
- **Higher power density reduces cost**

LA Electrolyzer Balance of Plant (BOP) Analysis

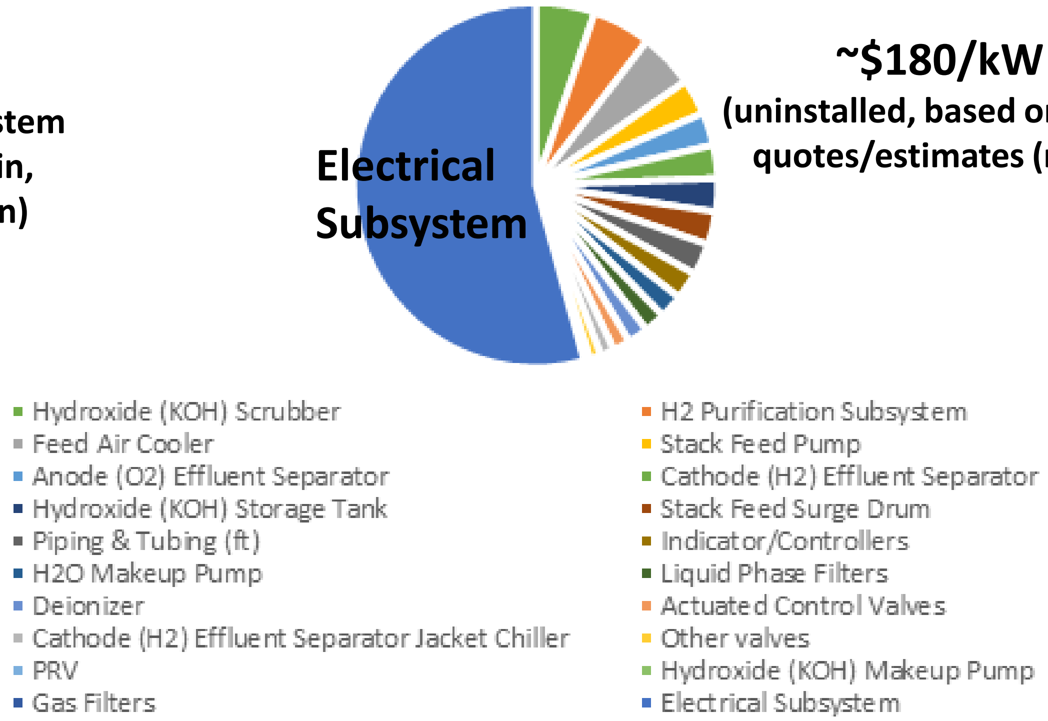
Preliminary Results: Cost Analysis in Progress

2014 E4tech BOP Cost Breakdown [32]



~$455/kW
(based on $1512/kW system price, 40% gross margin, 50% stack cost fraction)

Preliminary SA BOP Cost Breakdown: 25MW BOP Module



~$180/kW Cost
(uninstalled, based on scaled price quotes/estimates (not DFMA))

Preliminary observations:

- **Electrical subsystem (rectification) is a major BOP cost contributor**
- **Economies of scale observed: what is largest practical BOP sizing?**
- **Use of BOP modularity will reduce cost but it is hard to reliably quantify**
- **Economies of manufacturing rate are less-beneficial when BOP-module size is large**

Cost Reduction Strategies/Thoughts (1)

	2014 E4tech Recommendations/Assessment [32]	SA Thoughts
Zero-Gap Configuration	Improves performance	
Scale-Up Cell Size	Lower waste	
Scale-Up Stack Size		Looking at 5MW (or greater) stacks
Scale-Up BOP Components	Benefits to 500kW – 1MW, then flatter curve	Benefits to ~25MW (under review)
Scale-Up Manufacturing Rate		Examine out to 10GW/year. Compare many small stacks or systems vs. fewer large stacks (Enapter approach)
System Efficiency	Already high efficiency. Focus on reducing cost of high-efficiency systems	
Lifetime	Already high lifetime (>60kh). Focus on reducing cost of high-lifetime, high-efficiency, low-cost systems	
Dynamic Operation	Need dynamic operation to provide grid services and capture that revenue stream	Can be a key factor in market capture (vs PEM) and competitive LCOH
Bubble Reduction	To improve effective electrode area. Options include: centrifugal, magnetic fields, ultrasound, microwave	

Cost Reduction Strategies/Thoughts (2)

	2014 E4tech Recommendations/Assessment [32]	SA Thoughts
Stack/System Improvements	Anticipate incremental improvement in stack and system engineering and manufacturing	
Multi-MW Systems	Demo of multi-MW stacks and systems with reduced footprints and easier commissioning	3MW+ stacks already demonstrated. Is 10MW stack practical?
Advanced Catalysts	To achieve increased current densities, controlled morphologies, physiochemical properties, and stability in alkaline environments	
Membrane	Lower crossover rates, increased life	Can H2 purity be increased?
Factory Builds		(Further) manufacturing cost reduction via streamlined factory builds
Modularity		(Further) manufacturing & installation cost reduction via increased modularity and commonization of parts/subsystems
Turn-Down		Does poor AL turn-down limit operations & markets?

Cost Reduction Strategies/Thoughts (3)

	From 2019 "Perspectives on Low-Temperature Electrolysis…" Ayers, Pivovar et al [33]
Materials	Replace high-cost interconnect materials
Integration	Component integration
Cell Design	Advanced cell designs to enable higher current density at the same voltage.
Stack Design	For pressurized systems: rotation of the stacks for improved gas separation
Improved Efficiency	Improve efficiency via: • Improve gas and water management with cell via optimization of electrode porosity and additives to improve wetting • higher–activity catalyst on both electrodes

Thank You!

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