Manufacturing Competitiveness Analysis for PEM and Alkaline Water Electrolysis Systems

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National Renewable Energy Laboratory
Fuel Cell Seminar and Energy Expo
11/08/2017
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
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

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Alkaline</th>
<th>PEM</th>
<th>Unit</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current Density</td>
<td>0.2 - 0.7</td>
<td>1.0 - 2.2</td>
<td>A/cm²</td>
<td></td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>60 – 80</td>
<td>50 – 84</td>
<td>°C</td>
<td></td>
</tr>
<tr>
<td>Electricity Consumption (Median)</td>
<td>50 – 73 (53)</td>
<td>47 – 73 (52)</td>
<td>kWh/kg-H₂</td>
<td>Electrolysis system only. Excluding storage, compression and dispensing</td>
</tr>
<tr>
<td>Min. Load</td>
<td>20 - 40%</td>
<td>3 – 10%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Startup Time from Cold to Min. Load</td>
<td>20 min - 60+</td>
<td>5 – 15</td>
<td>minutes</td>
<td></td>
</tr>
<tr>
<td>System Efficiency (LHV) (Median)</td>
<td>45-67% (63%)</td>
<td>45 – 71% (63%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>System Lifetime (Median)</td>
<td>20-30 (26)</td>
<td>10-30 (22)</td>
<td>Year</td>
<td></td>
</tr>
<tr>
<td>System Price</td>
<td>$760 – $1,100 ($930)</td>
<td>$1,200-$1,940 ($1,570)</td>
<td></td>
<td>Including power supply, system control and gas drying. Excluding grid connection, external compression, external purification and H₂ storage</td>
</tr>
</tbody>
</table>

Sources of data: Bertuccioli et al., 2014, NREL 2017
II PEM Electrolyzer - Functional Specs & System Design
PEM Electrolyzer System Design

City Water

Water Cleaner

Oxygen/DI Water

Phase Separator

Demister

Pump

Heat Exchanger

Transformer

Rectifier

High Voltage Supply

Electrolyzer Stack

Water/H₂ Separator

H₂ Low Pressure Storage

Back Pressure Regulator

Dryer

Controllable Valve

Demister

GDL = Porous Transport Layer

Stack components picture from greencarcongress.com

* Stack components picture from greencarcongress.com
## Derived Functional Specifications

<table>
<thead>
<tr>
<th>Stack Power</th>
<th>10</th>
<th>20</th>
<th>50</th>
<th>100</th>
<th>200</th>
<th>500</th>
<th>1,000</th>
<th>2,000</th>
<th>5,000</th>
<th>10,000</th>
<th>kW</th>
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<tr>
<td>single cell amps</td>
<td>1224</td>
<td>A</td>
<td></td>
<td></td>
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<tr>
<td>current density</td>
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<tr>
<td>reference voltage</td>
<td>1.619</td>
<td>V</td>
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<tr>
<td>power density</td>
<td>2.913</td>
<td>W/cm²</td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>Pt-Ir loading- Anode</td>
<td>7.0</td>
<td>g/m²</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>PGM loading Cathode</td>
<td>4.0</td>
<td>g/m²</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>single cell power</td>
<td>1981.0</td>
<td>W</td>
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<td></td>
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</tr>
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</table>

### Assumptions

<table>
<thead>
<tr>
<th>Part</th>
<th>Assumptions</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Membrane</td>
<td>Nafion 117 (Purchased)</td>
<td>PFSA (PEEK, PBI)</td>
</tr>
<tr>
<td>Pt</td>
<td>Pt-price= 1500/tr.oz</td>
<td>DOE Current value</td>
</tr>
<tr>
<td>CCM</td>
<td>Spray Coating</td>
<td>Platinum loadings: Anode= 7g/m² (Pt) Cathode= 4g/m² (Pt-Ir)</td>
</tr>
<tr>
<td>Porous Transport Layer</td>
<td>Sintered porous titanium Ti-price= $4.5/kg</td>
<td>Porosity=30%</td>
</tr>
<tr>
<td>Seal/Frame</td>
<td>Screen printed PPS-40GF or PEEK seal</td>
<td>Seal: 0.635 cm from each side for MEA bonding</td>
</tr>
<tr>
<td>Plates</td>
<td>Stainless steel 316L</td>
<td>Coated (plasma Nitriding)</td>
</tr>
</tbody>
</table>
III  Alkaline Electrolyzer - Functional Specs & System Design
**Alkaline Electrolyzer System**

- **Phase Separator**
- **Heat Exchanger**
- **Pump**
- **KOH + H₂O**
- **O₂**
- **Combustible Gas Detector**
- **Water Cleaner**
- **City Water**
- **High Voltage Supply**
- **Transformer**
- **Rectifier**
- **Flow Direction**
- **Controllable Valve**
- **Demister**
- **Dryer**
- **H₂ Low Pressure Storage**
- **Back Pressure Regulator**

**Equations:**

\[
\text{H}_2 + \text{H}_2\text{O} + \text{KOH} \\
\text{O}_2 + \text{H}_2\text{O} + \text{KOH} \\
\text{H}_2\text{O} + \text{KOH} \\
\]

**Flow Directions:**

- \( \text{O}_2 + \text{H}_2\text{O} + \text{KOH} \)
- \( \text{H}_2\text{O} + \text{KOH} \)
- \( \text{H}_2\text{O} + \text{KOH} \)

**Diagram Components:**

- **Alkaline Electrolyzer Stack**
- **Electrolyte Flow Direction**
- **Flow Direction**
- **Electrolyte Flow Direction**

**Preliminary**
## Alkaline Electrolyzer - Functional Specs

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

### System rated power (kW)

<table>
<thead>
<tr>
<th>Electrolyte</th>
<th>10</th>
<th>20</th>
<th>50</th>
<th>100</th>
<th>200</th>
<th>500</th>
<th>1,000</th>
<th>2,000</th>
<th>5,000</th>
<th>10,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂O+ 30% KOH</td>
<td>150</td>
<td>150</td>
<td>150</td>
<td>150</td>
<td>150</td>
<td>150</td>
<td>150</td>
<td>150</td>
<td>150</td>
<td>150</td>
</tr>
</tbody>
</table>

### 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)

Coil - Stainless Steel 316L ➔ Blanking ➔ Stamping ➔ Cleaning (Chemical Bath)

N₂ Gas + High Voltage and Temperature

Plasma Nitriding ➔ Cleansing ➔ Plasma Nitriding Furnace ➔ Final Plate

Bipolar Plate Cost ($/pcs) - 200 kW system

Bipolar Plate Cost ($/pcs) - 1 MW system
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

Stack Assembly Cost ($/kW)- 200 kW

Stack Assembly Cost ($/kW)- 1 MW

Stack Assembly Cost ($/kW)- 200 kW

Stack Assembly Cost ($/kW)- 1 MW

65 kg H₂/day

385 kg H₂/day
Alkaline - Raney Nickel Electrodes

Process Flow Diagram

- **Ni-Sheets**
  - Thickness = ½mm

- **Degreasing**

- **PVD**
  - Ar Sputtering
  - To remove NiO from the surface

- **Leaching**
  - 1% NaOH
  - 2 hr @RT
  - 10% NaOH
  - 4 hr @100°C
  - 10% NaOH
  - 20 hr @RT

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

Electrode Cost ($/pcs) - 200 kW system

Electrode Cost ($/pcs) - 1 MW system

Electrode Cost ($/kW) - 200 kW system

Electrode Cost ($/kW) - 1 MW system

Preliminary
Manufacturing Cost of Electrolyzer Stacks

• Alkaline electrolyzer stacks have larger cost in $/kg-H₂

• 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 Nm³/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

Chart 1: Annual Fuel Cell Car and Bus Sales by Region, World Markets: 2015-2024

(Source: Navigant Research)
International Manufacturer of Onsite Hydrogen Production System

This map can be accessed from https://maphub.net/mayas111/Onsite-H2-Production-Equipment
PEM Electrolysis
### PEM - Functional Specifications

<table>
<thead>
<tr>
<th>System</th>
<th>Manufacturer</th>
<th>Hydrogenics</th>
<th>Proton OnSite</th>
<th>Proton OnSite</th>
<th>Proton OnSite</th>
<th>Proton OnSite</th>
<th>Giner</th>
<th>Proton OnSite</th>
<th>Siemens</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrolysis type</td>
<td>PEM (Proton Exchange Membrane)</td>
<td>PEM (Proton Exchange Membrane)</td>
<td>PEM (Proton Exchange Membrane)</td>
<td>PEM (Proton Exchange Membrane)</td>
<td>PEM (Proton Exchange Membrane)</td>
<td>PEM (Proton Exchange Membrane)</td>
<td>PEM (Proton Exchange Membrane)</td>
<td>PEM (Proton Exchange Membrane)</td>
<td>PEM (Proton Exchange Membrane)</td>
<td>PEM (Proton Exchange Membrane)</td>
</tr>
<tr>
<td>Rated stack Consumption</td>
<td>7.20</td>
<td>14.40</td>
<td>14.00</td>
<td>28.00</td>
<td>40.00</td>
<td>45.00</td>
<td>160.00</td>
<td>250.00</td>
<td>1250.00</td>
<td>kW</td>
</tr>
<tr>
<td>Startup time: millisecond scale</td>
<td>&lt; 10 sec</td>
<td>sec</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Hydrogen purity (dep. on operating point):</td>
<td>99.9995%</td>
<td>99.9995%</td>
<td>99.9995%</td>
<td>99.9995%</td>
<td>99.9995%</td>
<td>99.9995%</td>
<td>99.9995%</td>
<td>99.9995%</td>
<td>99.9995%</td>
<td>kW/Nm³</td>
</tr>
<tr>
<td>System Efficiency</td>
<td>6.70</td>
<td>6.70</td>
<td>7.30</td>
<td>7.00</td>
<td>6.80</td>
<td>7.50</td>
<td>6.25</td>
<td>5.56</td>
<td>kWh/Nm³</td>
<td></td>
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<tr>
<td>Net Production Rate</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>6</td>
<td>6</td>
<td>30.59</td>
<td>40</td>
<td>225</td>
<td>Nm³/h</td>
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<tr>
<td>Net Production Rate (scfh)</td>
<td>38</td>
<td>76</td>
<td>76</td>
<td>152</td>
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<td>228</td>
<td>1162</td>
<td>152</td>
<td>8,550</td>
<td>scfh</td>
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<td>Net Production Rate (kg/day)</td>
<td>2.16</td>
<td>4.32</td>
<td>4.31</td>
<td>8.63</td>
<td>12.94</td>
<td>12.95</td>
<td>66.00</td>
<td>86.30</td>
<td>485.46</td>
<td>kg/day</td>
</tr>
<tr>
<td>kW per kg/day ratio</td>
<td>3.34</td>
<td>3.34</td>
<td>3.25</td>
<td>3.24</td>
<td>3.09</td>
<td>3.48</td>
<td>2.42</td>
<td>2.90</td>
<td>2.57</td>
<td>kW per kg/day</td>
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<tr>
<td>Turndown Ratio</td>
<td>0 to 100%</td>
<td>to 100% net product delivery (Automatic)</td>
<td>to 100% net product delivery (Automatic)</td>
<td>to 100% net product delivery (Automatic)</td>
<td>10:1</td>
<td>10-100%</td>
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<tr>
<td>Output pressure</td>
<td>Up to 7.9</td>
<td>Up to 7.9</td>
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<td>bar</td>
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<tr>
<td>Feed Water</td>
<td>Up to 7.9</td>
<td>Up to 7.9</td>
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<td></td>
<td></td>
<td></td>
<td>bar</td>
</tr>
<tr>
<td>Power Supply</td>
<td>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.</td>
<td>380 to 480 VAC, 3 phase, 50 or 60 Hz</td>
<td>380 to 480 VAC, 3 phase, 50 or 60 Hz</td>
<td>380 to 480 VAC, 3 phase, 50 or 60 Hz</td>
<td>420-480 VAC, 3 phase, 60 Hz, 112 FLA</td>
<td>400VAC 50Hz</td>
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<tr>
<td>Cooling strategy</td>
<td>Air Cooled</td>
<td>Air Cooled</td>
<td>Liquid cooled 8.1 kW</td>
<td>Liquid cooled 16.1 kW</td>
<td>Liquid cooled 23.7 kW</td>
<td>Air or Liquid</td>
<td>Air Cooled</td>
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<tr>
<td>Operating Temperature</td>
<td>5 to 40</td>
<td>5 to 40</td>
<td>5 to 60</td>
<td>5 to 60</td>
<td>5 to 60</td>
<td>-23 to 46</td>
<td>5 to 35</td>
<td>°C</td>
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<tr>
<td>Hydrogen quality 5.0:</td>
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<td>Hydrogen production under nominal load:</td>
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<td>Life cycle design:</td>
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<tr>
<td>CE Approved</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other Specs</td>
<td>Circular cells with 300 cm²</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Dimensions</td>
<td>0.75 X 0.66 X 1.17</td>
<td>1.30 X 1.00 X 1.25</td>
<td>180 cm x 81 cm x 191 cm</td>
<td>180 cm x 81 cm x 191 cm</td>
<td>180 cm x 81 cm x 191 cm</td>
<td>2.18 X0.84 X1.91</td>
<td>0.85 X 1.05 X 1.65</td>
<td>6.3 X 3.10 X 3.00</td>
<td>mXmXm</td>
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<tr>
<td>Weight</td>
<td>250</td>
<td>275</td>
<td>682</td>
<td>858</td>
<td>908</td>
<td>900</td>
<td>260</td>
<td>17000</td>
<td>kg</td>
<td></td>
</tr>
</tbody>
</table>
CCM Slot-Die Coating Process

**Cathode**

- Ink Tank
- Ink Pump
- Slot-die coater
- Drying Oven
- QC Station
- Optical System
- Scanner
- Membrane and Backing Layer Spool

**Anode**

- Ink Tank
- Ink Pump
- Slot-die coater
- Drying Oven
- QC Station
- Optical System
- Scanner
- Substrate Spool
CCM Slot-Die Coating Process

Final CCM

Cathode layer

Membrane

Heat Nip Rollers

Anode layer

Substrate

Anode Coated Side

Cathode Coated Side

Substrate Removal

QC Station

Scanner

Final CCM Spool
Powder Metallurgy for GDL

GDL or Porous Transport Layer

Fig. 2. SEM (a) and optical microscope (b) micrographs of a porous current collectors made of sintered titanium spherical-particles.
Proposed Cell/Plates/Seal Structure

Cathode Plate

Seals

Frame

MEA Cell

Anode Plate

Porous Ti GDL

Cathode Layer

Nafion Membrane

Anode Layer
## Balance of Plant Cost (Parts Only)

<table>
<thead>
<tr>
<th>System Size kW</th>
<th>10 kW</th>
<th>20 kW</th>
<th>50 kW</th>
<th>100 kW</th>
<th>200 kW</th>
<th>500 kW</th>
<th>1,000 kW</th>
<th>2,000 kW</th>
<th>5,000 kW</th>
<th>10,000 kW</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Baseline Cost ($)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Cost ($/kW)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Power Supplies
- **Quote (AEG)**
- **Quote**
  - **DC Voltage Transducer**
  - **DC Current Transducer**

### Deionized Water Circulation
- **Oxygen Separator Tank**
- **Circulation Pump**
- **Polishing Pump**
- **Piping**
- **Valves, Instrumentation**

### Hydrogen Processing
- **Dryer Bed**
- **Hydrogen Separator**
- **Tubing**
- **Valves, Instrumentation**

### Controls
- **Class I, Div 2, Group B rating drives up prices**

### Cooling
- **Plate heat exchanger**
- **Cooling pump**
- **Valves, Instrumentation**
- **Piping**
- **Dry cooler**

### Miscellaneous
- **Valve air supply – nitrogen or compressed air**
- **Ventilation and safety requirements**
  - **Combustible gas detectors**
  - **Exhaust ventilation**

### Total
- **Grand Total ($)**
- **Cost ($/kW)**
Power Supply Cost

Price_{\text{Magna}} = 531.59 \times \text{kVA} + 12007
R^2 = 0.9895

Price_{\text{AEG}} = 134.2x + 63250
R^2 = 0.9976

Price_{\text{Other}} = 385.88x^{0.9333}
R^2 = 0.9645
Balance of Plant Cost (Parts Only)

BOP Cost Breakdown - 200kW System
- Power Supplies: 29%
- Deionized Water Circulation: 4%
- Hydrogen Processing: 24%
- Cooling: 11%
- Miscellaneous: 4%

BOP Cost Breakdown - 500kW System
- Power Supplies: 48%
- Deionized Water Circulation: 21%
- Hydrogen Processing: 21%
- Cooling: 8%
- Miscellaneous: 2%

BOP Cost Breakdown - 1MW System
- Power Supplies: 49%
- Deionized Water Circulation: 19%
- Hydrogen Processing: 22%
- Cooling: 1%
- Miscellaneous: 7%

BOP Cost Breakdown - 10MW System
- Power Supplies: 57%
- Deionized Water Circulation: 21%
- Hydrogen Processing: 19%
- Cooling: 3%
- Miscellaneous: 0%
Alkaline Electrolysis
Cells are assembled electrically in series, hydraulically in parallel.
# Commercial Alkaline Electrolyzers

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Pure Energy Center</th>
<th>Hydrogenics HySTAT 15</th>
<th>Hydrogenics HySTAT 30</th>
<th>Hydrogenics HySTAT 60</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model Number</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electrolysis type</td>
<td>Alkaline</td>
<td>Alkaline</td>
<td>Alkaline</td>
<td>Alkaline</td>
<td></td>
</tr>
<tr>
<td>Rated stack Consumption</td>
<td>22.30</td>
<td>145.00</td>
<td>270.00</td>
<td>515.00</td>
<td>kW</td>
</tr>
<tr>
<td>Electrolyte</td>
<td>H₂O+ 30% KOH</td>
<td>H₂O+ 30% KOH</td>
<td>H₂O+ 30% KOH</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydrogen purity (dep. on operating point):</td>
<td>99.3-99.8</td>
<td>99.9</td>
<td>99.9</td>
<td>99.9</td>
<td>%</td>
</tr>
<tr>
<td>System Efficiency</td>
<td>5.58</td>
<td>4.90</td>
<td>5.20</td>
<td>4.90</td>
<td>kWh/Nm³</td>
</tr>
<tr>
<td>Net Production Rate</td>
<td>4</td>
<td>6 to 15</td>
<td>12 to 30</td>
<td>24 to 60</td>
<td>Nm³/h</td>
</tr>
<tr>
<td>Net Production Rate (scfh)</td>
<td>227 to 570</td>
<td>456 to 1140</td>
<td>912 to 2280</td>
<td></td>
<td>scfh</td>
</tr>
<tr>
<td>Net Production Rate (kg/day)</td>
<td>13 to 32</td>
<td>26 to 65</td>
<td>52 to 130</td>
<td></td>
<td>kg/day</td>
</tr>
<tr>
<td>kWh per kg ratio</td>
<td>62.08</td>
<td>54.52</td>
<td>57.86</td>
<td>54.52</td>
<td>kWh/kg</td>
</tr>
<tr>
<td>Turndown Ratio</td>
<td>10-100%</td>
<td></td>
<td></td>
<td></td>
<td>%</td>
</tr>
<tr>
<td>Output pressure</td>
<td>up to 12 bar</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>bar</td>
</tr>
<tr>
<td>Feed Water</td>
<td>Deionized water</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fresh water demand:</td>
<td>ltr / Nm³ H₂</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inlet water pressure</td>
<td>barg</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Relative Humidity</td>
<td>&lt;95</td>
<td>&lt;96</td>
<td>&lt;96</td>
<td></td>
<td>%</td>
</tr>
<tr>
<td>Power Supply</td>
<td>400 VAC; 50 Hz</td>
<td></td>
<td>3*400 VAC 50 Hz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cooling strategy</td>
<td>Air or liquid</td>
<td>Water cooled</td>
<td>Water cooled</td>
<td>Water cooled</td>
<td></td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>5-35</td>
<td></td>
<td></td>
<td></td>
<td>°C</td>
</tr>
<tr>
<td>Certification</td>
<td>CE Approved</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other Specs</td>
<td>Other Specs</td>
<td>Dimensions 1.65</td>
<td>6</td>
<td>3.22X1.81X2.53</td>
<td>mXmXm</td>
</tr>
<tr>
<td>Weight</td>
<td>260</td>
<td>3800</td>
<td></td>
<td></td>
<td>kg</td>
</tr>
</tbody>
</table>
Electrode Materials

- **Decomposition (corrosion) to cost ratio**
  - Zinc, iron and brass would perform better than other metals

- From the **current density** perspective
  - Silver, iron and nickel would perform better than other metals

_Symes et al., 2013_
Alkaline Electrolyzer Power Density

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

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

<table>
<thead>
<tr>
<th>Current density</th>
<th>Today</th>
<th>2015</th>
<th>2020</th>
<th>2025</th>
<th>2030</th>
</tr>
</thead>
<tbody>
<tr>
<td>A/cm²</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alkaline</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Central</td>
<td>0.3</td>
<td>0.4</td>
<td>0.7</td>
<td>0.7</td>
<td>0.8</td>
</tr>
<tr>
<td>Range</td>
<td>0.2 - 0.4</td>
<td>0.2 - 0.7</td>
<td>0.3 - 1.0</td>
<td>0.5 - 1.0</td>
<td>0.6 - 1.0</td>
</tr>
<tr>
<td>PEM</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Central</td>
<td>1.7</td>
<td>1.9</td>
<td>2.2</td>
<td>2.4</td>
<td>2.5</td>
</tr>
<tr>
<td>Range</td>
<td>1.0 - 2.0</td>
<td>1.2 - 2.2</td>
<td>1.6 - 2.5</td>
<td>1.6 - 2.8</td>
<td>1.6 - 3.0</td>
</tr>
</tbody>
</table>
Alkaline Electrolyzer Configuration

Monopolar

\[ U_M = U_{\text{cell}} \]

\[ + \rightarrow I_M \]

\[ I_{\text{cell}} \rightarrow I_{\text{cell}} \rightarrow I_{\text{cell}} \]

anode (+)  cathode (+)  diaphragm

Bipolar

\[ U_M = I_{\text{cell}} \]

\[ + \rightarrow U_{\text{cell}} \]

\[ - \rightarrow U_{\text{cell}} \]

\[ + \rightarrow - \rightarrow + \rightarrow - \rightarrow + \rightarrow - \]

anode (+)  cathode (+)  diaphragm
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 plates due to the bubbles in the conventional design.

Phillips and Dunnill, 2016
Stack Components

- 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

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 (H₂) adsorbed on the nickel surface.


**Table 1: Comparison of HER Catalysts**

<table>
<thead>
<tr>
<th>Electrode</th>
<th>Performance</th>
<th>Conditions</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pt/C</td>
<td>0.6 mA cm⁻² exchange current density</td>
<td>0.1 M KOH, thin film</td>
<td>Ref 31</td>
</tr>
<tr>
<td>Polished Ni</td>
<td>422 mV overpotential at 75 A cm⁻²</td>
<td>0.5 M KOH, SCE, 3.14 mm² disk electrode</td>
<td>Ref 60</td>
</tr>
<tr>
<td>Core</td>
<td>6.1 x 10⁻⁴ mA cm⁻² exchange current</td>
<td>0.1 M NaOH w/o ME nanoflakes</td>
<td>Ref 34</td>
</tr>
<tr>
<td>Ni₅Co₇/C</td>
<td>9.1 x 10⁻³ mA cm⁻² exchange current</td>
<td>0.1 M NaOH w/o ME nanoflakes</td>
<td>Ref 34</td>
</tr>
<tr>
<td>Raney Ni</td>
<td>100 mV overpotential at 500 mA cm⁻²</td>
<td>28 wt% KOH, 80°C</td>
<td>Ref 47</td>
</tr>
<tr>
<td>Ni₅₄W₃₆</td>
<td>1.6 x 10⁻⁴ mA cm⁻² exchange current density</td>
<td>0.1 M KOH, thin film</td>
<td>Ref 51</td>
</tr>
<tr>
<td>MnNi₂₂Co₂₂Mn₀₄₄Al₀₂₇</td>
<td>88 mV overpotential at 200 mA cm⁻²</td>
<td>Ni foam substrate and Ni–Mo coating, 30 wt% KOH</td>
<td>Ref 54</td>
</tr>
<tr>
<td>LaNi₄₅Si₃₁</td>
<td>84 mV overpotential at 200 mA cm⁻²</td>
<td>Ni foam substrate and Ni–Mo coating, 30 wt% KOH</td>
<td>Ref 54</td>
</tr>
<tr>
<td>Ti₅Ni</td>
<td>60 mV overpotential at 200 mA cm⁻²</td>
<td>Ni foam substrate and Ni–Mo coating, 30 wt% KOH</td>
<td>Refs 12 and 54</td>
</tr>
<tr>
<td>Ni₆₀Mo₄₀</td>
<td>29 mA cm⁻² 59 mV overpotential at 250 mA cm⁻²</td>
<td>30 wt% KOH, 70°C, nanocrystalline fcc, mechanical alloyed</td>
<td>Ref 62</td>
</tr>
<tr>
<td>Ni–S</td>
<td>39.2 mA cm⁻² 90 mV overpotential at 150 mA cm⁻²</td>
<td>28 wt% NaOH, electrodeposited, thiourea</td>
<td>Ref 40</td>
</tr>
<tr>
<td>Fe–Mo</td>
<td>20.4 x 10⁻³ mA cm⁻²</td>
<td>Fe(20%–Mo(60%), 1 M NaOH, 25°C</td>
<td>Ref 57</td>
</tr>
<tr>
<td>Ni–(Ebonex-Ru)</td>
<td>597 mA cm⁻² 156 mV at 100 mA cm⁻²</td>
<td>Ni–Ti₅O₃Ru, 1 M NaOH at 25°C</td>
<td>Ref 63</td>
</tr>
<tr>
<td>Pd/Au</td>
<td>NA</td>
<td>Pd/Au(111)</td>
<td>Ref 56</td>
</tr>
<tr>
<td>Ni–Sn</td>
<td>NA</td>
<td>Alloy coating deposited on Ni mesh</td>
<td>Ref 64</td>
</tr>
<tr>
<td>Ni–S–Co</td>
<td>70 mV at 150 mA cm⁻²</td>
<td>80°C, electrodeposition</td>
<td>Ref 41</td>
</tr>
<tr>
<td>Ni₃Al</td>
<td>1.9 mA cm⁻²</td>
<td>6 M KOH</td>
<td>Ref 36</td>
</tr>
<tr>
<td>Ni₃Al–Mo</td>
<td>13 mA cm⁻²</td>
<td>6 M KOH</td>
<td>Ref 37</td>
</tr>
<tr>
<td>Ni–S–Mn</td>
<td>97.5 mA cm⁻²</td>
<td>30% KOH, amorphous alloy</td>
<td>Ref 43</td>
</tr>
<tr>
<td>Ni₈₈P₁₆C₃</td>
<td>2.11 mA cm⁻² 125.4 mA at 250 mA cm⁻²</td>
<td>1 M NaOH, 25°C</td>
<td>Ref 39</td>
</tr>
<tr>
<td>Ni₆₂Fe₃₅C₃</td>
<td>24.5 mA cm⁻² 112.6 mA at 250 mA cm⁻²</td>
<td>1 M NaOH, 25°C</td>
<td>Ref 65</td>
</tr>
<tr>
<td>Ni–Co</td>
<td>29 mA cm⁻²</td>
<td>0.5 M NaOH, 25°C</td>
<td>Ref 66</td>
</tr>
<tr>
<td>Fe₉₄P₄C₂</td>
<td>0.075 mA cm⁻²</td>
<td>1 M NaOH, 25°C</td>
<td>Ref 45</td>
</tr>
</tbody>
</table>

HER: Hydrogen Evolution Reaction  
Table from Bodner et al., 2015
# Membranes

<table>
<thead>
<tr>
<th>Membrane</th>
<th>Ion Exchange Capacity</th>
<th>Conductivity (mS/cm)</th>
<th>Thickness</th>
<th>Cell Current Density† (mA/cm²)</th>
<th>Manufacturer</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tokuyama A201</td>
<td>1.68 ± 0.08</td>
<td>40</td>
<td>28 μm</td>
<td>400 @1.8V</td>
<td>Tokuyama, (Japan)</td>
<td>Bodner et al., (2015) Ren et al., (2014)</td>
</tr>
<tr>
<td>Nafion 117</td>
<td>0.91</td>
<td>90.6</td>
<td>178 μm</td>
<td>n/a</td>
<td>DuPont (USA)</td>
<td>Ren et al., (2014)</td>
</tr>
<tr>
<td>m-PBI poly(2,2-(m-phenylene)-5,5-bibenzimidazole)</td>
<td>n/a</td>
<td>100</td>
<td>50-60 μm</td>
<td>400 @2V</td>
<td>Danish Power Systems (Denmark), Advent (USA)</td>
<td>Kraglund et al., (2016)</td>
</tr>
<tr>
<td>Zirfon™ Perl UTP 500 (polyphenylene sulphide/zirconium oxide)</td>
<td>Ionic resistance≤0.3 Ω.cm² at 30†</td>
<td>500 ± 50 μm</td>
<td>250 @2V</td>
<td></td>
<td>Agfa-Gevaert (Belgium)</td>
<td></td>
</tr>
<tr>
<td>xxx</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

† Assuming 30% KOH
# Membrane

## TABLE 2 | Comparison of Different AEMs for Alkaline Electrolysis Cells

<table>
<thead>
<tr>
<th>Membrane</th>
<th>Conductivity</th>
<th>Current density</th>
<th>Cathode</th>
<th>Anode</th>
<th>High frequency resistance</th>
<th>Thickness</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zero gap diaphragm with 30 wt% KOH</td>
<td>$54.3 \times 10^{-2}$/ (Ω cm) at 25°C$^a$</td>
<td>470 mA cm$^{-2}$ at 1.8 V, 50°C</td>
<td>Mo/Raney Ni</td>
<td>Co$_3$O$_4$/Raney Ni</td>
<td>NA</td>
<td>NA</td>
<td>Refs 19, $^a$84</td>
</tr>
<tr>
<td>Tokuyama A201</td>
<td>0.04 S cm$^{-1}$ at 23°C$^b$</td>
<td>399 mA cm$^{-2}$ at 1.8 V, 50°C</td>
<td>Pt black</td>
<td>IrO$_2$</td>
<td>0.23 Ω cm$^2$ at 2.0 V, 50°C</td>
<td>28 μm</td>
<td>Refs 19, $^b$85</td>
</tr>
<tr>
<td>Seleion AMV</td>
<td>$2.52 \times 10^{-1}$ S cm$^{-1}$</td>
<td>90 mA/cm$^{-2}$ at 2.0 V, 30°C</td>
<td>Ni/Zn/S coated Ni foam</td>
<td>Graphene oxide-coated NiO</td>
<td>NA</td>
<td>120 μm</td>
<td>Ref 61</td>
</tr>
<tr>
<td>QAPS</td>
<td>$&gt;10^{-2}$ S cm$^{-1}$</td>
<td>0.4 A/cm$^{-2}$ at 1.8–1.85 V, 70°C</td>
<td>Ni–Mo</td>
<td>Ni–Fe</td>
<td>NA</td>
<td>70 μm</td>
<td>Ref 48</td>
</tr>
<tr>
<td>qPVB/Cl</td>
<td>$2.7 \times 10^{-2}$ S cm at 60°C</td>
<td>250 mA cm$^{-2}$ at 2.24 V, 55°C</td>
<td>Ni nano powder</td>
<td>Cu$<em>{0.7}$Co$</em>{2.3}$O$_4$</td>
<td>0.37 Ω cm$^2$ at 60°C</td>
<td>70 μm</td>
<td>Ref 81</td>
</tr>
<tr>
<td>QA-ETFE$^c$, QPDTB ionomer</td>
<td>138.7 mS cm$^{-1}$ (ionomer: 0.059 S cm$^{-1}$ at 50°C)</td>
<td>100 mA cm$^{-2}$ at 1.9 V, 22°C</td>
<td>Ni nanopowder</td>
<td>Cu$<em>{0.7}$Co$</em>{2.3}$O$_4$</td>
<td>0.85 Ω cm$^2$ at 22°C full MEA resistance</td>
<td>88.4 μm$^c$</td>
<td>Refs 83, $^c$82</td>
</tr>
<tr>
<td>LDPE-g-VBC</td>
<td>17 mS cm$^{-1}$ at 60°C</td>
<td>300 mA cm$^{-2}$ at 2.1 V, 45°C$^*$</td>
<td>NA</td>
<td>NA</td>
<td>0.3–0.43 Ω cm$^2$ at 45°C</td>
<td>NA</td>
<td>Ref 80</td>
</tr>
</tbody>
</table>

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

* This table is copied from Bodner et al., 2015
### BOM- 1st Generation Monomers

<table>
<thead>
<tr>
<th>Materials</th>
<th>Suppliers</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pyridine dicarboxylic acids (2,4-, 2,5-, 2,6- and 3,5-PDA)</td>
<td>Sigma-Aldrich Chemical Co. Matrix Scientific Alpha Aeser Chemical Co.</td>
<td>$126 for 100mg $91 for 25 g $212 for 500 g</td>
</tr>
<tr>
<td>3,3′,4,4′-Tetraaminobiphenyl (TAB)</td>
<td>Sigma-Aldrich Chemical Co. TCI America Tetra-Hedron</td>
<td>$250 for 25 g $126 for 25 g $380 for 100 g</td>
</tr>
<tr>
<td>Polyphosphoric acid (115%) (PPA)</td>
<td>Sigma-Aldrich Chemical Co.</td>
<td>$60 for 1 kg</td>
</tr>
<tr>
<td>Ammonia Hydroxide</td>
<td>Sigma-Aldrich Chemical Co.</td>
<td>$340 for 6X2.5L</td>
</tr>
<tr>
<td>Distilled water</td>
<td>Sigma-Aldrich Chemical Co.</td>
<td></td>
</tr>
<tr>
<td>Phosphoric Acid (Conc. 85% for doping)</td>
<td>Duda Energy</td>
<td>$40 per gallon</td>
</tr>
<tr>
<td>Dimethylacetamide (DMAc)</td>
<td>Sigma-Aldrich Chemical Co. Alpha Aeser Chemical Co.</td>
<td>$542 for 6L $82.5 for 2.5L</td>
</tr>
</tbody>
</table>
Manufacturing of PBI-based Membrane

1. **DMAC**
2. **Milling & Mixing (PDA, TAB, PPA)**
3. **Melting @ 200°C**
4. **Casting Process**
5. **Hydrolysis @ RT & RH=40±5%**
6. **Doping in Phosphoric Acid**
7. **Drying @ RT**

---

**Figure 1.** State diagram of the PPA sol–gel preparation process. Image from Xiao et al., 2005
Casting Process

- **Melting Container**
- **Slot-die coater**
- **Regulator**
- **Drying Oven**
- **QC Station**
- **Control Unit** (Temp., Pressure, Viscosity)
- **PDA** (Pyridine Dicarboxylic Acids)
- **TAB** (Tetra-Amino Biphenyl)
- **PPA** (PolyPhosphoric Acid)

**Process Flow**:
1. **PPA** → **Melting Container**
2. **Melting Container** → **Slot-die coater**
3. **Slot-die coater** → **Drying Oven**
4. **Drying Oven** → **QC Station**
5. **Control Unit** (Temp., Pressure, Viscosity)
6. **Substrate Removal**
7. **Winding Roll**

**Backward Flow**:
1. **QC Station** → **Control Unit**
2. **Control Unit** → **Drying Oven**
3. **Drying Oven** → **Slot-die coater**
4. **Slot-die coater** → **Melting Container**
5. **Melting Container** → **PPA**
• 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

**Nickel Bipolar Plate Cost ($/pcs)**

- **200 kW system**
  - Annual Production Rate (unit/yr)
  - Cost breakdown:
    - Scrap/Waste
    - Building
    - Energy
    - Variable
    - Capital
    - Direct Labor
    - Direct Materials

- **1 MW system**
  - Annual Production Rate (unit/yr)
  - Cost breakdown:
    - Scrap/Waste
    - Building
    - Energy
    - Variable
    - Capital
    - Direct Labor
    - Direct Materials

**Nickel Bipolar Plate Cost ($/kW)**

- **200 kW system**
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    - Energy
    - Variable
    - Capital
    - Direct Labor
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- **1 MW system**
  - Annual Production Rate (unit/yr)
  - Cost breakdown:
    - Scrap/Waste
    - Building
    - Energy
    - Variable
    - Capital
    - Direct Labor
    - Direct Materials

**Production Rates**

- **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
PEM and Alkaline Electrolyzer Capital Cost

**Capital cost for Alkaline systems**

![Graph showing capital cost for Alkaline systems over years 2010 to 2030. The graph includes data points and lines indicating central case and range for the years.]

**Capital cost for PEM systems**

![Graph showing capital cost for PEM systems over years 2010 to 2030. The graph includes data points and lines indicating central case and range for the years.]

<table>
<thead>
<tr>
<th>System cost (1)</th>
<th></th>
<th>Today</th>
<th>2015</th>
<th>2020</th>
<th>2025</th>
<th>2030</th>
</tr>
</thead>
<tbody>
<tr>
<td>EUR/kW</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Alkaline</td>
<td>Central</td>
<td>1,100</td>
<td>930</td>
<td>630</td>
<td>610</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Range</td>
<td>1,000 - 1,200</td>
<td>760 - 1,100</td>
<td>370 - 900</td>
<td>370 - 850</td>
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<tr>
<td></td>
<td>PEM</td>
<td>Central</td>
<td>2,090</td>
<td>1,570</td>
<td>1,000</td>
<td>870</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Range</td>
<td>1,860 - 2,320</td>
<td>1,200 - 1,940</td>
<td>700 - 1,300</td>
<td>480 - 1,270</td>
</tr>
</tbody>
</table>

(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

Potential Cost Reductions in PEM Electrolyzer Cost

<table>
<thead>
<tr>
<th>Component</th>
<th>Base Cost ($/kW)</th>
<th>Economies of Scale</th>
<th>Power Electronics Cost</th>
<th>Improvement in Power Density</th>
<th>Pt Loading</th>
<th>Membrane Cost</th>
<th>Final Cost ($/kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delta</td>
<td>0</td>
<td>165</td>
<td>16</td>
<td>30</td>
<td>11</td>
<td>281</td>
<td>281</td>
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<tr>
<td>Bottom</td>
<td>0</td>
<td>356</td>
<td>340</td>
<td>310</td>
<td>291</td>
<td>281</td>
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<tr>
<td>BOP</td>
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<td>$0</td>
<td>$0</td>
<td>$0</td>
<td>$0</td>
<td>$211</td>
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<tr>
<td>Balance of Stack</td>
<td>$26</td>
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<td>$0</td>
<td>$0</td>
<td>$0</td>
<td>$0</td>
<td>$10</td>
</tr>
<tr>
<td>Assembly &amp; End-Plates</td>
<td>$13</td>
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<td>$0</td>
<td>$0</td>
<td>$0</td>
<td>$0</td>
<td>$4</td>
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<tr>
<td>Bipolar Plates</td>
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<td>$0</td>
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<td>$0</td>
<td>$5</td>
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<tr>
<td>Frame</td>
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<td>$0</td>
<td>$0</td>
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<td>$0</td>
<td>$3</td>
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<tr>
<td>Porous Transport Layer</td>
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<td>$0</td>
<td>$0</td>
<td>$0</td>
<td>$6</td>
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<tr>
<td>CCM</td>
<td>$100</td>
<td>$0</td>
<td>$0</td>
<td>$0</td>
<td>$0</td>
<td>$0</td>
<td>$51</td>
</tr>
</tbody>
</table>

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/cm² to 3.50 W/cm²)
- Pt loading: reducing PGM loading from 11 g/m² to 5 g/m²
- Membrane cost: 20% cost reduction
Effect of Electrolyzer Capital Cost on H₂ Cost

![Bar Chart showing the cost of H₂ production at different capacity factors and costs of electricity.]

- **Capacity Factor**
  - 97%
  - 40%

- **Cost of Electricity**
  - $6.6/kWh
  - $2/kWh
  - $1/kWh
  - $2/kWh
  - $1/kWh

- **Capital Cost**
  - $521/kW
  - $521/kW
  - $521/kW
  - $356/kW
  - $356/kW

- **Cost of H₂ Production ($/kg)**
  - 3.45
  - 2.86
  - 2.34
  - 2.27
  - 1.74

- **Legend**
  - Other costs
  - Feedstock cost
  - Fixed O&M cost
  - Capital cost
Comparative Cost Analysis (Stack Only)

Stack Cost ($/kW) - 200 kW System

- Balance of Stack (Housing, Manifolds, Wiring, Insulations, etc.)
- Assembly & End-Plates
- Bipolar Plates
- Frame
- Porous Transport Layer
- Electrode Assembly

Relative Cost:
- PEM: 79%
- Alkaline: 81%
- PEM: 80%
- Alkaline: 82%
- PEM: 82%
- Alkaline: 89%
- PEM: 89%

Stack Cost:
- 10 kg H₂/day
- 10 kg H₂/day
- 20 kg H₂/day
- 20 kg H₂/day
- 50 kg H₂/day
- 50 kg H₂/day
- 100 kg H₂/day
- 100 kg H₂/day
- 1,000 kg H₂/day
- 1,000 kg H₂/day

Annual Production Rate (unit/yr):
- PEM
- PEM
- Alkaline
- PEM
- Alkaline
- PEM
- Alkaline
- PEM
- Alkaline

65 kg H₂/day
48 kg H₂/day
Comparative Cost Analysis (Stack Only)

Stack Cost ($/kW) - 1 MW System

- **Relative Cost**
  - Bipolar Plates: 67%
  - Frame: 62%
  - Electrode Assembly: 61%
  - Balance of Stack: 62%

- **Cost ($/kW)**
  - 0
  - 50
  - 100
  - 150
  - 200
  - 250

- **Annual Production Rate (unit/yr)**
  - 10 PEM
  - 10 Alkaline
  - 20 PEM
  - 20 Alkaline
  - 50 PEM
  - 50 Alkaline
  - 100 PEM
  - 100 Alkaline
  - 1,000 PEM
  - 1,000 Alkaline

- **Production Rates**
  - 385 kg H₂/day
  - 250 kg H₂/day

Preliminary
Alkaline vs. PEM Electrolyzer

- Alkaline electrolyzer stacks have larger cost in $/kg-H₂ basis and in $/kW basis