Manufacturing Competitiveness Analysis for Hydrogen Refueling Stations and Electrolyzers

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National Renewable Energy Laboratory
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DOE Hydrogen and Fuel Cells Program
2018 Annual Merit Review and Peer Evaluation Meeting

Project ID # MN017

This presentation does not contain any proprietary, confidential, or otherwise restricted information.
Overview

Timeline

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

Technical Barriers

Cross-Cutting Fuel Cell Barriers
- F. Manual Stack Assembly
- I. Lack of Standardized Balance-of-Plant Component

Hydrogen Generation by Water Electrolysis
- F. Capital Cost
- K. Manufacturing

Budget

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

Collaborators

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

• To develop detailed bottom-up manufacturing cost analysis for key systems/parts in the hydrogen refueling station (HRS).

• To identify cost drivers for key systems in the hydrogen refueling stations (e.g., compressors, storage tanks, dispenser, coolers and heat exchanger).

• To identify cost drivers for onsite hydrogen production systems (PEM and alkaline electrolyzers).

• To investigate effect of economies of scale and learning experience on the cost of the onsite hydrogen production systems.
Approach

Global assumptions (e.g., capital, tool life, building life, etc.)

Local assumptions by country (e.g. labor, energy cost, building cost, etc.)

Manufacturing cost model (PEM and Alkaline electrolyzer)

Minimum sustainable price (Mf’g cost, balance of plant, profit margin, etc.)

Compare to other cost studies (H2A, E4Tech, etc.)

Benchmark with existing/future commercial products

HRS rollouts 2005-2017 (PNNL, CEC, NEDO, HySUT, NOW, CEP, etc.)

HRS trade flows (HRS developers, part suppliers)

Supply chain maps HRS technology (gaseous, liquid, onsite) system components

Qualitative factors (e.g. skilled labor, existing supply chain, regulations, tax policy, etc.)

Quantifying these factors (e.g. learning rate, scrap rate reduction, etc.)

Key outputs

1) HRS and onsite H₂ system manufacturing costs and minimum sustainable prices
2) International trade flows & supply chain maps
3) Estimation of future HRS technologies cost and effects on H₂ price
Accomplishment - Global HRS Trade Flows

Updated Map

Green/Blue colors within same country represent domestic shipments only

Source of data: PNNL 09/2017, Alternative fuel data center, 2017
NREL analysis 2017
Comparison Between PEM And Alkaline Electrolyzers

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

<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>Power Density</td>
<td>0.32 - 1.12</td>
<td>1.4 - 3.52</td>
<td>W/cm²</td>
<td>Reference voltage = 1.6 volt</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</td>
<td>47 – 73</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%</td>
<td>45 – 71%</td>
<td>(63%) (63%)</td>
<td></td>
</tr>
<tr>
<td>System Lifetime (Median)</td>
<td>20-30</td>
<td>10-30</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>Including power supply, system control and gas drying. Excluding grid connection, external compression, external purification and H₂ storage</td>
<td></td>
</tr>
</tbody>
</table>

Sources of data: Bertuccioli et al., 2014, NREL analysis 2017
Stack is the core of the PEM electrolysis system. Balance of plant parts usually outsourced from reliable vendors.
Accomplishment - PEM Electrolyzer
Functional Specifications for Analysis

Current and power densities are key parameters in the cell design

<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>
</tr>
</thead>
<tbody>
<tr>
<td>single cell amps</td>
<td>1224</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>A</td>
</tr>
<tr>
<td>current density</td>
<td>1.80</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>A/cm²</td>
</tr>
<tr>
<td>reference voltage</td>
<td>1.619</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>V</td>
</tr>
<tr>
<td>power density</td>
<td>2.913</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>W/cm²</td>
</tr>
<tr>
<td>Pt-Ir loading- Anode</td>
<td>7.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>g/m²</td>
</tr>
<tr>
<td>PGM loading Cathode</td>
<td>4.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>g/m²</td>
</tr>
<tr>
<td>single cell power</td>
<td>1981.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>W</td>
</tr>
<tr>
<td>Cells per system</td>
<td>5</td>
<td>10</td>
<td>25</td>
<td>50</td>
<td>101</td>
<td>252</td>
<td>505</td>
<td>1010</td>
<td>2524</td>
<td>5048</td>
<td>cells</td>
</tr>
<tr>
<td>stacks per system</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>4</td>
<td>10</td>
<td>20</td>
<td>stacks</td>
</tr>
<tr>
<td>cells per stack</td>
<td>5</td>
<td>10</td>
<td>25</td>
<td>50</td>
<td>101</td>
<td>252</td>
<td>252</td>
<td>252</td>
<td>252</td>
<td>252</td>
<td>cells</td>
</tr>
</tbody>
</table>

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

<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:</td>
</tr>
<tr>
<td>Porous Transport Layer</td>
<td>Sintered porous titanium</td>
<td>Anode= 7g/m² (Pt)</td>
</tr>
<tr>
<td>Seal/Frame</td>
<td>Screen printed PPS-40GF or PEEK</td>
<td>Cathode= 4g/m² (Pt-Ir)</td>
</tr>
<tr>
<td>Plates</td>
<td>Stamped stainless steel 316L</td>
<td>Coated plates (plasma Nitriding)</td>
</tr>
</tbody>
</table>

PPS-40GF: poly Phenylene Sulfide (40% Glass fiber filled)
Accomplishment - Alkaline Electrolyzer
Functional Specifications for Analysis

Current and power densities are key parameters in the cell design

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

† See Vogt et al., 2014

<table>
<thead>
<tr>
<th>Stack power (kW)</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>Avg. H₂ production rate (Nm³/h)</td>
<td>2</td>
<td>4</td>
<td>10</td>
<td>15</td>
<td>22</td>
<td>56</td>
<td>110</td>
<td>220</td>
<td>550</td>
<td>1,100</td>
</tr>
<tr>
<td>Avg. H₂ production rate (kg/day)</td>
<td>4</td>
<td>9</td>
<td>22</td>
<td>32</td>
<td>48</td>
<td>120</td>
<td>237</td>
<td>475</td>
<td>1,187</td>
<td>2,373</td>
</tr>
<tr>
<td>Total plate area (cm²)</td>
<td>3,000</td>
<td>10,000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total plate solid area (cm²)</td>
<td>400</td>
<td>800</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electrode active area (cm²)</td>
<td>2,600</td>
<td>9,200</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electrolyte</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H₂O+ 30% KOH</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single cell amps</td>
<td>520</td>
<td>520</td>
<td>520</td>
<td>520</td>
<td>520</td>
<td>520</td>
<td>520</td>
<td>520</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Current density</td>
<td>0.20</td>
<td>0.20</td>
<td>0.20</td>
<td>0.20</td>
<td>0.20</td>
<td>0.20</td>
<td>0.20</td>
<td>0.20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reference voltage</td>
<td>1.68</td>
<td>1.68</td>
<td>1.68</td>
<td>1.68</td>
<td>1.68</td>
<td>1.68</td>
<td>1.68</td>
<td>1.68</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power density</td>
<td>0.336</td>
<td>0.336</td>
<td>0.336</td>
<td>0.336</td>
<td>0.336</td>
<td>0.336</td>
<td>0.336</td>
<td>0.336</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single cell power</td>
<td>873.6</td>
<td>873.6</td>
<td>873.6</td>
<td>873.6</td>
<td>873.6</td>
<td>873.6</td>
<td>3091.2</td>
<td>3091.2</td>
<td>3091.2</td>
<td>3091.2</td>
</tr>
<tr>
<td>Cells per system</td>
<td>12</td>
<td>23</td>
<td>58</td>
<td>115</td>
<td>229</td>
<td>573</td>
<td>324</td>
<td>647</td>
<td>1,618</td>
<td>3,235</td>
</tr>
<tr>
<td>Stacks per system</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>4</td>
<td>9</td>
<td>17</td>
</tr>
<tr>
<td>cells per stack</td>
<td>12</td>
<td>23</td>
<td>58</td>
<td>115</td>
<td>115</td>
<td>191</td>
<td>162</td>
<td>162</td>
<td>180</td>
<td>191</td>
</tr>
</tbody>
</table>

Additional Parasitic
- Air blower/ Liquid pump: 0.3 | 0.5 | 1.5 | 2 | 3 | 7 | 10 | 15 | 30 | 50 |
- Other paras. loads: 0.2 | 0.3 | 0.5 | 1 | 1.5 | 3 | 5 | 8 | 10 | 15 |
- Parasitic loss: 0.5 | 0.8 | 2.0 | 3.0 | 4.5 | 10.00 | 15.00 | 23.00 | 40.00 | 65.00 |

Functional Cell Design

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

PVD: physical vapor deposition
PPS-40GF: poly Phenylene Sulfide (40% Glass fiber filled)
Accomplishment - PEM - Bipolar Plate Cost Model

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

Case Hardening (Nitriding)

1. Coil - Stainless Steel 316L
2. Blanking
3. Stamping
4. Cleaning (Chemical Bath)
5. Plasma Nitriding
6. Plasma Nitriding Furnace
7. Cleansing
8. Final Plate

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

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

- Scrap/Waste
- Building
- Energy
- Variable
- Capital
- Direct Labor
- Direct Materials

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

- Scrap/Waste
- Building
- Energy
- Variable
- Capital
- Direct Labor
- Direct Materials
Stack assembly is still semi-manual and there is good room for improvements (robots, flexible assembly line)

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

Image from: Mayyas et al., 2016
Stack assembly is a labor-intensive process. Capital and building cost dominate at low production rates.

Stack Assembly Cost ($/kW) - 200 kW

Stack Assembly Cost ($/kW) - 1 MW

65 kg H₂/day

385 kg H₂/day
U.S. based manufacturers have advantages of 1) longer experience (i.e., learning rate), and 2) lower energy cost except for China and Mexico (still has smaller effect in the stack cost)

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

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

385 kg H₂/day
Larger production rates could also play role in reducing the cost (economies of scale for the stack modules) and balance of plant (not shown in these charts)

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

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

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

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

<table>
<thead>
<tr>
<th>Currently Shipped</th>
<th>Shipped globally</th>
<th>Shipped globally</th>
<th>Shipped regionally</th>
<th>Shipped globally</th>
<th>Shipped globally</th>
</tr>
</thead>
<tbody>
<tr>
<td><em><em>Value Share</em> [Cumulative]</em>*</td>
<td>15% [15%]</td>
<td>7% [22%]</td>
<td>5% [27%]</td>
<td>73% [100%]</td>
<td>n/a [100%]</td>
</tr>
</tbody>
</table>

### U.S. Strengths
- n/a
- R&D Innovation
- Manufacturing experience
- Educated workforce

### Areas Need Work
- Supply chain security for critical materials (e.g., platinum, Iridium, etc.)
- Cost of manufacturing
- Automation/advanced manufacturing (e.g., roll-to-roll)
- Low-cost labor availability (compared to China and Mexico)

- Educated workforce
- Synergistic industries and clustering (benefiting from fuel cell manufacturing)

- Availability of suppliers
- Import and export policies (no tariffs)

- Availability of manufacturers
- Support from federal and state programs (e.g., California and Northeast hydrogen infrastructure)

- Quality and performance of products
- Cost of manufacturing
- Automation of assembly process

- Standardization of parts
- Cost of power electronics

- Lack of coordinated incentives and facilitation in some states

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

• Alkaline water electrolyzers have lower current and power densities, but have lower system cost (per kW basis) because of lower electrode materials cost (no precious materials) and larger cell size

• PEM electrolyzers have higher power density which requires smaller stack areas in relative to alkaline stack. This could contribute to lower stack costs with economies of scale

• U.S. based manufacturers have advantages of low energy cost, availability of skilled workers, and intellectual property

• Emerging manufacturing technologies (e.g. roll-to-roll catalyst coating, plates nitriding/coating, full automated assembly line, etc.) in association with economies of scale will have great impact on the capital cost of onsite H₂ production systems and cost of H₂ generation
Remaining Challenges and Barriers

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

• Involve more organizations (industry, part suppliers, regulation agencies, etc.) in the hydrogen refueling station study

• Make new collaboration with industry in the ongoing project (manufacturing competitiveness analysis for onsite hydrogen production systems)

• Expand the cost study framework to cover CAPEX and OPEX and to compare cost of HRS to gas stations

• Benchmark our results with actual installations in several countries/regions

• There is a strong need to study manufacturing cost for balance of plant parts (e.g. AC-DC rectifier shares >20% of total PEM electrolysis system cost)
Proposed Future Work

• Complete manufacturing cost analysis onsite $\text{H}_2$ production systems
  
  — PEM electrolyzers
  
  — Alkaline electrolyzers

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

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

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

“Any proposed future work is subject to change based on funding levels.”
There was no discussion about the cost of a “gasoline refueling station,” which, although clearly less, is far from zero. It is interesting that gasoline is almost always dispensed from buried tanks, which are conveniently out of sight and have no footprint.

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

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

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

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

– This assumption is based on some discussions we had with fuel cell and H₂ compressor manufacturers. It’s sort of rule-of-thumb and may not get a wider acceptance in the fuel cell community. Also, we found something similar to this assumption when we collected the quotes from different vendors with different discount ranging between 5-35% in most cases.

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

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

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

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

• David Hart, Franz Lehner, E4Tech, United Kingdom
  – Provided data for manufacturing cost analysis for PEM and alkaline electrolyzers

• Syed Saba, Forschungszentrum Jülich (FZJ), Germany
  – Provided cost data for PEM electrolyzer to validate our cost model

• Brian James, Strategic Analysis Inc.
  – Provided cost data for PEM electrolyzers

• Kevin Harrison, Bryan Pivovar, Guido Bender, Mark Ruth, Owen Smith, NREL
  – Provided critical inputs for cost model and discussed cost model results

• Industry stakeholders: provided estimates for dispenser cost (AEG and Magna Power (power supplies), Grundfos (water pumps), etc.)
Summary

• **Relevance**: to provide a framework for technoeconomic and supply chain analyses for hydrogen refueling stations and onsite hydrogen production systems

• **Approach**: Bottom-up cost analysis cost models and detailed supply chain maps.

• **Technical Accomplishments and Progress**:  
  – Manufacturing cost models for onsite hydrogen production systems (alkaline and PEM)  
  – Trade flow maps for global HRS’s

• **Collaboration**: E4Tech, FZJ Institute

• **Proposed Next-Year Research**:  
  – Complete manufacturing cost models for alkaline electrolyzer  
  – Investigate effect of qualitative factors in the manufacturing competitiveness
Technology Transfer Activities

- Not applicable for this cost analysis
Thank You

www.nrel.gov

PR-6A20-71304
Technical Back-Up Slides
Titanium layer performs better in the corrosive environment inside the stack. Could have lower cost at higher production rates.

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

Annual production rate represents number of produced electrolyzers per year (200 kW system).
Balance of Plant Cost - PEM (Parts Only)

Parts only at low order quantities. Discounts are expected with larger quantities.
**Sensitivity Analysis – Alkaline Electrolyzer Stack**

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

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

### 1 MW Alkaline Electrolyzer Stack

*(Cost = $133/kW @ 10 units/yr)*

<table>
<thead>
<tr>
<th>Yield</th>
<th>Power Density</th>
<th>Wages</th>
<th>Membrane Cost</th>
<th>Electrode Material Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>+20%</td>
<td>-7</td>
<td>$5</td>
<td>$5</td>
<td>$1</td>
</tr>
<tr>
<td>-20%</td>
<td>$32</td>
<td>$15</td>
<td>-5</td>
<td>-$1</td>
</tr>
</tbody>
</table>

### 1 MW Alkaline Electrolyzer Stack

*(Cost = $58/kW @ 1,000 units/yr)*

<table>
<thead>
<tr>
<th>Yield</th>
<th>Power Density</th>
<th>Wages</th>
<th>Membrane Cost</th>
<th>Electrode Material Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>+20%</td>
<td>-3</td>
<td>-9</td>
<td>$5</td>
<td>$1</td>
</tr>
<tr>
<td>-20%</td>
<td>$15</td>
<td>$13</td>
<td>-5</td>
<td>-$1</td>
</tr>
</tbody>
</table>