U.S. Clean Energy Hydrogen and Fuel Cell Technologies: A Competitiveness Analysis

Presenter: P. I. - Patrick Fullenkamp

GLWN - Westside Industrial Retention & Expansion Network

Date: June 6, 2017
Time: 1:45:00 PM
Project ID: MN014

Photo of Mirai by Patrick Fullenkamp

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Overview

Timeline

- Project Start Date: 06/01/15
- Project End Date: 05/31/19

Budget

Total Project Budget: $803,253
- Total Recipient Share: $337,970
- Total Partner Share: $373,912

Total DOE Funds Spent*: $711,882
* as of 3/31/16

Partners

- GLWN – Project Lead
- Strategic Analysis, Inc.
- DJW Technologies
- E4tech

Barriers Addressed

Note: Barriers currently under reevaluation

- A. Lack of high volume MEA processes (includes catalyst, membrane, GDL)
- B. Lack of high speed bipolar plate manufacturing processes
- K. Lack of low cost fabrication techniques for storage tanks
- I. Lack of Standardized Balance-of-Plant Components
Relevance

- Project falls under the Clean Energy Manufacturing Initiative (CEMI) mission to increase
  - domestic manufacture of clean energy products
  - energy productivity

- Competitiveness is largely driven by cost, thus we examine
  - Current and projected cost
  - Supply chain evolution per feedback from OEM & Suppliers
  - Global trade flows

- Outcome of this project will
  - Aid DOE/CEMI in identifying strategic investments
  - Lay out prospective future supply chain per feedback
  - Identify technology areas for R&D investment
Project Summary: To study the state of hydrogen and fuel cell manufacturing, and to characterize the factors that impact the global competitiveness of fuel cell and hydrogen related manufacturing.
Approach: Project Methodology

- **Historical perspective** on automotive supply chain evolution
- **Cost analysis** to show components contributing most to the final automotive FC system (AFCS)
- **Structured interview process** to gather data on the status of development of different components
- **Interviews and plant visits** in the most important regions to allow visualization and in-depth discussion on relevant development needs
- **Detailed data on the fuel cell industry**, including annual shipment numbers and different regional support
- **Value stream mapping** to identify the flows within the relevant manufacturing processes
- **Implications for the U.S.**
Approach: Actors by Region; key suppliers; cost breakdowns

Study focused on five key components: >60% of total cost

<table>
<thead>
<tr>
<th>COMPONENT</th>
<th>USA</th>
<th>Asia</th>
<th>Europe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bipolar Plates</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Membrane</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Gas Diffusion Layer</td>
<td>1*</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Catalyst Ink</td>
<td>1*</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Pressure Vessels</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Other items included in cost but not studied:
- **H₂ storage balance of system** (regulator, valve, tubing, fittings, system controller, and fill port);
- **fuel cell stack components** (gaskets, end plates, current collectors, compression bands, stack insulation housing, stack assembly, stack conditioning);
- **fuel cell balance of plant** (CEM & motor controller, H₂ sensors, coolant & air handling components, fuel system components, humidifier, system controller). See slides 57-58 for further details.
# Accomplishments: Industry Scorecard Technology and Manufacturing Readiness by Region

Global industry ready for 10k systems per year. High volume capabilities need further development.

## Technology Readiness

<table>
<thead>
<tr>
<th></th>
<th>Bipolar Plate</th>
<th>Catalyst</th>
<th>Gas Diffusion layer</th>
<th>Membrane</th>
<th>H2 Vessel</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-10k</td>
<td>HIGH</td>
<td>HIGH</td>
<td>HIGH</td>
<td>HIGH</td>
<td>HIGH</td>
</tr>
</tbody>
</table>

## Manufacturing Readiness

<table>
<thead>
<tr>
<th></th>
<th>Bipolar Plate</th>
<th>Catalyst</th>
<th>Gas Diffusion layer</th>
<th>Membrane</th>
<th>H2 Vessel</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-10k</td>
<td>H-M HIGH HIGH HIGH H-M HIGH HIGH HIGH</td>
<td>H-M HIGH HIGH HIGH</td>
<td>H-M HIGH HIGH HIGH</td>
<td>H-M HIGH HIGH HIGH</td>
<td>H-M HIGH HIGH HIGH</td>
</tr>
</tbody>
</table>

### Readiness Legend:

- **HIGH**  - Currently sufficient to produce to stated demand
- **HIGH TO MODERATE**  - Capability and capacity exist, although no current production demonstrated at stated demand
- **MODERATE**  - Requires some advancements or capital investment to produce to stated demand
- **MODERATE TO LOW**  - Requires some advancements capital investment, and no current production demonstrated at stated demand
- **LOW**  - Requires major advancements or major capital investments to produced to stated demand
## Accomplishments: U.S. Competitiveness in Manufacturing and Innovation

<table>
<thead>
<tr>
<th>BPP</th>
<th>Membrane</th>
<th>Catalyst</th>
<th>GDL</th>
<th>Vessel</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Near</td>
<td>Far</td>
<td>Near</td>
<td>Far</td>
</tr>
<tr>
<td>Manuf.</td>
<td>Forming Low</td>
<td>Forming High</td>
<td>Ionomer Low</td>
<td>Ionomer Mod</td>
</tr>
<tr>
<td>Potential</td>
<td>Coating Mod-Low</td>
<td>Coating High</td>
<td>Support Mod</td>
<td>Support Mod</td>
</tr>
<tr>
<td>Joining</td>
<td>Joining Low</td>
<td>Joining High</td>
<td>R2R High-Mod</td>
<td>R2R High-Mod</td>
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<tr>
<td>Innov.</td>
<td>Forming Low</td>
<td>Forming High</td>
<td>Ionomer High-Mod</td>
<td>Ionomer High-Mod</td>
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<tr>
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<td>Support High</td>
<td>Support High</td>
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<tr>
<td>Joining</td>
<td>Joining High</td>
<td>Joining High</td>
<td>R2R High-Mod</td>
<td>R2R High-Mod</td>
</tr>
</tbody>
</table>

### Manufacturing Potential
- **HIGH**
- **HIGH TO MODERATE**
- **MODERATE**
- **MODERATE TO LOW**
- **LOW**

High, Medium, or Low potential for U.S. manufacturing competitiveness due to combination of extent of manufacturing infrastructure, access to appropriate labor, extent of similar or enabling businesses/technologies, and overall manufacturing business climate.

### Innovation Potential
- **HIGH**
- **HIGH TO MODERATE**
- **MODERATE**
- **MODERATE TO LOW**
- **LOW**

High, Medium, or Low potential for U.S. to be innovative and advance the state-of-the-art in a given sector due to combination of existing research focus, extent of research facilities, prevalence of related technologies, enabling natural resources, and company/national commitment to development.
Accomplishments: HFC Jobs & Investment at 100k vehicles (stacks & PV’s) / year

<table>
<thead>
<tr>
<th>Component</th>
<th>Direct Labor Jobs</th>
<th>Investment</th>
<th>Units / year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bipolar Plate (BPP)</td>
<td>30 - 40</td>
<td>$80M Capex, $36M Facilities</td>
<td>37M</td>
</tr>
<tr>
<td>Catalyst</td>
<td>20 - 40</td>
<td>$2.4M Capex, $14M Facilities</td>
<td>1,800kg Pt</td>
</tr>
<tr>
<td>Gas Diffusion Layer (GDL)</td>
<td>35 - 50</td>
<td>$30M Capex, $13M Facilities</td>
<td>2.4M m²</td>
</tr>
<tr>
<td>Membrane</td>
<td>35 – 50</td>
<td>$7M Capex, $5M Facilities</td>
<td>2.4M m²</td>
</tr>
<tr>
<td>Pressure Vessel (PV)</td>
<td>160 – 190</td>
<td>$33M Capex, $74M Facilities</td>
<td>100,000</td>
</tr>
</tbody>
</table>

Direct Labor Jobs estimates are shown in a range and represents the number of unskilled, skilled, and line supervisors but does not include other indirect support staff or outside jobs that are supported by component manufacturers. Outside jobs estimated at 6x.
Accomplishments: Options to Improve U.S. Fuel Cell Competitiveness

• No single nation is clearly dominant. **Success will depend on the rapidity and extent of U.S. participation in the global FC marketplace.**

**U.S. strengths:**
• High-technology domestic automotive industry
• Superb innovation ecosystem
• Access to educated workforce
• Reliable & low cost electrical energy supply

**U.S. disadvantages:**
• Growth in Asia is much faster. **Demand will increasingly be met by Asian suppliers, who then will out-compete U.S. suppliers.**
• Lack of Coordinated Incentives/Facilitation
• High Corporate tax rate
• Increasing R&D Investments outside the U.S.

**Options include:**
• Further demand-side support to help ‘pull through’ supplier base
• Support for strategic, job creating and high value added manufacturing
Accomp: Map of one possible OEM transition in responsibility for the production of the AFCS

The OEM manufacturing transitions suggested in this slide are consistent with the transitions in the Product-Life-Cycle of an emerging technology; however, the Growth and Maturity stages will be strongly dependent on the manufacturing culture of the different OEMs.
Accomp: Cost breakdown by processing step and operating expense (bipolar plate example)

Bipolar plate costs are driven by Capex and stainless steel costs for the stamping operation.
Accomplishments: Discounted Cash Flow Analysis (bipolar plate example)

Access to low-cost stamping equipment (either through low-cost capital or equipment discounts) and materials, and economies are competitive advantages.
Accomp: Value Stream Map (bipolar plate example)

Value Stream Map is a hybrid of process flow used in DFMA and inputs from suppliers and OEMs. VSM outputs are used for cost breakdown analysis and as a cost reduction tool.
Accomplishments: Regional Cost Breakdown for Bipolar plate

Global stamped commodity, new Capex for presses drives burden

Bipolar Plate Regional Cost Breakdown

USA: $3.25 Quote
- Profit: $0.05
- Engineering: $0.10
- SGA: $0.80
- Burden: $1.02
- Labor: $0.04
- Materials: $1.04

Europe: $3.50 Quote
- Profit: $0.05
- Engineering: $0.10
- SGA: $0.80
- Burden: $1.13
- Labor: $0.06
- Materials: $1.06

Asia: $3.38 Quote - China
- Profit: $0.04
- Engineering: $0.10
- SGA: $0.80
- Burden: $1.02
- Labor: $0.04
- Materials: $1.03
Accomplishments: Regional Cost Breakdown for Catalyst, GDL, Membrane, PV

Major Cost differentiators of all 5 key components are Material & Burden

- **Cathode Catalyst Regional Cost Breakdown**
  - USA: $5.00
  - Europe: $5.25
  - Asia: $5.50

- **GDL Regional Cost Breakdown**
  - USA: $5.75
  - Europe: $6.00
  - Asia: $6.25

- **Membrane Regional Cost Breakdown**
  - USA: $6.25
  - Europe: $6.50
  - Asia: $6.75

- **Pressure Vessel Regional Cost Breakdown**
  - USA: $16.80
  - Europe: $17.00
  - Asia: $17.20

*Department of Energy Award No. DE-EE-0006935*
Accomp: Motivations for Developing a Fuel Cell Economy by Country

Big global drivers: Zero polluting emissions (in cities especially), and reduced fleet-wide CO₂ requirements

- **Japan**: strongly shaped by its lack of natural energy resources and diversification from fossil fuel. Fuel cells and hydrogen energy are seen as an opportunity for industry
- **Korea**: similar to the Japanese motivation
- **European Union**: industrial strategy and jobs, but also responds to strong climate policy ambitions
- **Germany**: industrial and innovation policy (automotive industry strong), air quality and climate change
- **Canada**: early leader, innovation and climate change policy very supportive again
- **China**: (1) to reduce reliance on overseas technology and expertise, (2) to increase the potential for high-value jobs, (3) cleaner and better-performing industry and (4) high-value exports
- **United States**: many states support fuel cell technology:
  - 30 include fuel cells or hydrogen as eligible resources in Renewable Portfolio Standards.
  - 32 permit net metering of fuel cells.
  - 25 offer funding: rebates, grants, loans, bonds, PACE financing, or public benefits funding.
  - 16 states provide personal, corporate, property and/or sales tax incentives for fuel cells.
Accomplishments: U.S. Competitiveness in 5 Key Components

Bipolar Plate: Europe and Asia hold the lead in bipolar plate technology. U.S. behind in forming and coating. U.S. prospects high in far term

Catalyst: Europe (Umicore, Johnson Matthey) and Asia (Tanaka) are currently the world leaders in fuel cell catalyst technology. U.S. prospects are low to moderate in far term

GDL: Four main competitors predominate and are divided among Europe (SGL, Freudenberg), Asia (Toray), and the U.S. (Avcarb). Overall, the outlook for U.S. GDL production and innovation competitiveness is rated moderate

Membrane: The U.S. currently holds the global lead in membrane technology

Pressure Vessel: pressure vessel competitiveness is divided into carbon fiber production and vessel fabrication. Both areas ripe for technology advancement; the U.S. is active in both areas. The prospect for U.S. production and innovation competitiveness is rated high
“As much as the analysis seems to be relying on the SA cost analysis, it would be good to see, in future reviews, how the results of this competitiveness project have affected the analysis or methodology used by SA.”

• SA costing was the base starting point with this project providing more support data from: detailed drawings for each of the 5 key components, direct feedback from suppliers during interviews to refresh models, cost guidance quotations on all components.

“The presentation does not make clear how this project will assist DOE, beyond currently supported cost and market analyses. Supply chain decisions ultimately rest with OEMs, not DOE. It is not clear whether the project will output new technologies that need to be developed or parts or components that need to be redesigned to assist DOE.”

• This final report clearly defines the deliverables: reflects the current readiness feedback from stakeholders (OEMs & Suppliers) summarized in R-Y-G charts; reflects global and U.S. supplier competitiveness, strengths and opportunities for improvement; reflects a complete cost analysis with three tools (DFMA, CBA Cost Breakdown Analysis and VSM Value Stream Map), options to improve U.S. fuel cell competitiveness, provided a listing of 16 opportunities for DOE to pursue from applied to basic research.

“Dissemination of results as a final report may not be adequate. It would be unfortunate if valuable results were not more readily available or accessible to the community. Perhaps there are other approaches in addition to a report that might help garner interest and highlight results.”

• The full detailed report on the Competitiveness Analysis has been submitted to DOE FCTO in January 2017 and we are in process of making requested refinements. We plan to get the report out to all OEMs and Suppliers that participated and to the DOE standard distribution list. We are also in process of writing a Journal Article.
Collaborations

- **Strategic Analysis Inc.** – Subcontractor
  - DFMA cost analysis responsibility, part of global interview process and plant visits, updating cost models
- **E4tech** – Subcontractor
  - Annual Data collection, part of the interview process, and plant visits
  - Europe, Asia
- **DJW Technology** – Subcontractor
  - Supply Chain Evolution Summary, part of the interview process
- **Brent Fourman** – Subcontractor
  - Drawing Designer
- **Bowen Liu** – Subcontractor
  - Supporting China/Asian CBA, VSM, and plant visits
- **NREL** – data collaboration
- **Automotive OEMs (8) and Tier 1 suppliers (22)** – interview participants
Remaining Challenges and Barriers

- Global Competitiveness Analysis has been completed
- In the final 2 of 4 years provide the 2016 and 2017 Market Data in units, megawatts, revenue by application, by region of manufacture, by fuel cell technology
Proposed Future Work

- **Remainder of FY2017**
  - Work with DOE to obtain full approval and publication of Competitiveness Analysis report

- **FY2018 & FY2019**
  - Provide Market Data in both units, megawatts, and revenue by application, by region of manufacture, and by fuel cell technology
Technology Transfer Activities

This project has no technology transfer tasks.
• No single nation is clearly dominant regarding prospects for the long-term fuel cell market, but U.S. OEMs and manufacturers have fallen behind Japan and Europe in BPP, membrane, GDL, and catalyst (on par in H₂ vessels). The U.S. potential is broadly moderate to high, though with weaknesses in bipolar plate manufacturing and ionomers in the near term.

• U.S. has great depth in the science and technology of fuel cells, high quality in existing automotive industry and supply chain capability. California, in particular, has been a global driver of the fuel cell industry for two to three decades.

• The industry is only just beginning, and judicious investment now could reap benefits for many years to come.

• Increasing domestic fuel cell demand is viewed as a critical enabler of domestic fuel cell system production.

• U.S. OEMs and manufacturers need to re-start local development as they have fallen behind Japan and Europe in BPP, membrane, GDL, and catalyst (on par in H₂ vessels).

• Competitiveness Analysis complete, 2016 and 2017 years for market data.
Technical Back-Up Slides
Cathode Catalyst cost breakdown by processing step (left) and operating expense (right)
Cathode Catalyst Discounted Cash Flow Analysis
Gas Diffusion Layer cost breakdown by processing step (left) and operating expense (rt)
Gas Diffusion Layer Discounted Cash Flow Analysis
Gas Diffusion Layer Value Stream Map – U.S.

**Department of Energy**

**Award No. DE-EE-0006935**

**Gas Diffusion Layer Manufacturing Process**

U.S. Production at 100k Vehicles per Year

**Customer**
- Customer Demand: 10,182 m² Day

**Labor Summary**
- Rate: $25.00/hr

**Time Summary**
- Lead Time: 14 Day
- Total Value Added: 84 Sec
- Value Added Percent: 100 %
- Takt Time: 2 Sec

**Value Stream Diagram**
- **PTFE**
  - Activity Lead Time: 2 Wk
- **MPL INK**
  - Activity Lead Time: 2 Wk
- **Binder**
  - Activity Lead Time: 2 Wk
- **Carbon Fiber**
  - Activity Lead Time: 2 Wk
- **Resin**
  - Activity Lead Time: 2 Wk
- **Inert Gas**
  - Activity Lead Time: 2 Wk

**MPL COATING**
- Cycle Time: 12 Sec
- Qty Per Cycle: 51 m²
- Direct Labor: $0.083/m²
- Cumulative Cost: $0.333/m²

** IMPREGNATION COATING**
- Cycle Time: 12 Sec
- Qty Per Cycle: 1 m²
- Direct Labor: $0.083/m²
- Cumulative Cost: $0.417/m²

** SINTERING**
- Cycle Time: 12 Sec
- Qty Per Cycle: 1 m²
- Direct Labor: $0.083/m²
- Cumulative Cost: $0.50/m²

**PACKAGE and PREPARE FOR SHIPPING**
- Cycle Time: 12 Sec
- Qty Per Cycle: 1 m²
- Direct Labor: $0.083/m²
- Cumulative Cost: $0.58/m²

**PAPER MAKING**
- Cycle Time: 12 Sec
- Qty Per Cycle: 1 m²
- Direct Labor: $0.083/m²
- Cumulative Cost: $0.167/m²

**IMPRESSION COATING (Porosity)**
- Cycle Time: 12 Sec
- Qty Per Cycle: 1 m²
- Direct Labor: $0.083/m²
- Cumulative Cost: $0.250/m²

**OXIDATION / CARBONIZATION/ GRAPHITIZATION**
- Cycle Time: 12 Sec
- Qty Per Cycle: 1 m²
- Direct Labor: $0.083/m²
- Cumulative Cost: $0.250/m²

**SUPPLIER ORDER**
- Production Control

**GDL ORDER**

**Customer**
Membrane cost breakdown by processing step (left) and operating expense (rt)
Membrane Discounted Cash Flow Analysis

**10k veh/year**

- **Marginal Costs:**
  - China: $45.67
  - S. Korea: $46.88
  - Japan: $50.37
  - Germany: $52.35
  - US: $53.29
  - Mexico: $46.85

**Membrane Price Sensitivity at 10k Vehicles/Year**
(Mid-point based on U.S. inputs)

<table>
<thead>
<tr>
<th>Input</th>
<th>Base Case</th>
<th>$1000/hr (avg)</th>
<th>$1750/hr (avg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wages (all)</td>
<td>$7.68/hr</td>
<td>$7.68/hr (avg)</td>
<td>$7.68/hr (avg)</td>
</tr>
<tr>
<td>Equipment Discount</td>
<td>35%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Facilities Cost ($/m2)</td>
<td>$805/m2</td>
<td>$1900/m2</td>
<td>$1900/m2</td>
</tr>
<tr>
<td>Inflation</td>
<td>5.9%</td>
<td>5.9%</td>
<td>5.9%</td>
</tr>
<tr>
<td>Cost of Capital</td>
<td>14%</td>
<td>14%</td>
<td>14%</td>
</tr>
<tr>
<td>Installation Factor</td>
<td>12%</td>
<td>12%</td>
<td>12%</td>
</tr>
<tr>
<td>Tax</td>
<td>25%</td>
<td>40%</td>
<td>40%</td>
</tr>
<tr>
<td>Utility Rates</td>
<td>$0.058/kWh</td>
<td>$0.15/kWh</td>
<td>$0.15/kWh</td>
</tr>
</tbody>
</table>

**100k veh/year**

- **Marginal Costs:**
  - China: $22.47
  - S. Korea: $22.63
  - Japan: $23.56
  - Germany: $23.93
  - US: $23.73
  - Mexico: $22.83

**Membrane Price Sensitivity at 100k Vehicles/Year**
(Mid-point based on U.S. inputs)

<table>
<thead>
<tr>
<th>Input</th>
<th>Base Case</th>
<th>$2400/hr (avg)</th>
<th>$3200/hr (avg)</th>
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</thead>
<tbody>
<tr>
<td>Cost of Capital</td>
<td>14%</td>
<td>14%</td>
<td>14%</td>
</tr>
<tr>
<td>Equipment Discount</td>
<td>35%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Facilities Cost ($/m2)</td>
<td>$805/m2</td>
<td>$1900/m2</td>
<td>$1900/m2</td>
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<tr>
<td>Inflation</td>
<td>5.9%</td>
<td>5.9%</td>
<td>5.9%</td>
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<tr>
<td>Wages (all)</td>
<td>$7.68/hr</td>
<td>$7.68/hr (avg)</td>
<td>$7.68/hr (avg)</td>
</tr>
<tr>
<td>Tax</td>
<td>25%</td>
<td>40%</td>
<td>40%</td>
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<tr>
<td>Utility Rates</td>
<td>$0.058/kWh</td>
<td>$0.15/kWh</td>
<td>$0.15/kWh</td>
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</tbody>
</table>

*Minimum Sustainable Price*
Pressure Vessel cost breakdown by processing step (left) and operating expense (rt)
Pressure Vessel Discounted Cash Flow Analysis

**10k veh/year**

<table>
<thead>
<tr>
<th>Country</th>
<th>Pressure Vessel MSPP ($/kWh)</th>
<th>Margins</th>
<th>R&amp;D</th>
<th>Shipping &amp; Logistics</th>
<th>Utilities</th>
<th>Tooling</th>
<th>Labor</th>
<th>Maintenance</th>
<th>Materials</th>
<th>Capital Equipment</th>
<th>Facilities</th>
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<tbody>
<tr>
<td>China</td>
<td>$3,152</td>
<td>$3,152</td>
<td>$3,152</td>
<td>$3,152</td>
<td>$3,152</td>
<td>$3,152</td>
<td>$3,152</td>
<td>$3,152</td>
<td>$3,152</td>
<td>$3,152</td>
<td>$3,152</td>
</tr>
<tr>
<td>Japan</td>
<td>$3,592</td>
<td>$3,592</td>
<td>$3,592</td>
<td>$3,592</td>
<td>$3,592</td>
<td>$3,592</td>
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<td>$3,592</td>
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<tr>
<td>US</td>
<td>$3,674</td>
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<td>$3,674</td>
<td>$3,674</td>
<td>$3,674</td>
<td>$3,674</td>
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</tr>
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</table>

**Pressure Vessel Price Sensitivity at 10k Vehicles/Year**

<table>
<thead>
<tr>
<th>Cost of Capital</th>
<th>Material Discount</th>
<th>Facilities Cost ($/m²)</th>
<th>Wages (all)</th>
<th>Inflation</th>
<th>Tax</th>
<th>Equipment Discount</th>
<th>Installation Factor</th>
<th>Utility Rates</th>
</tr>
</thead>
<tbody>
<tr>
<td>$3,200</td>
<td>14%</td>
<td>$7.68/hr (avg)</td>
<td>$805/m²</td>
<td>0%</td>
<td>0%</td>
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*Minimum Sustainable Price

**100k veh/year**

<table>
<thead>
<tr>
<th>Country</th>
<th>Pressure Vessel MSPP ($/kWh)</th>
<th>Margins</th>
<th>R&amp;D</th>
<th>Shipping &amp; Logistics</th>
<th>Utilities</th>
<th>Tooling</th>
<th>Labor</th>
<th>Maintenance</th>
<th>Materials</th>
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<th>Facilities</th>
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**Pressure Vessel Price Sensitivity at 100k Vehicles/Year**

<table>
<thead>
<tr>
<th>Cost of Capital</th>
<th>Material Discount</th>
<th>Facilities Cost ($/m²)</th>
<th>Wages (all)</th>
<th>Inflation</th>
<th>Tax</th>
<th>Equipment Discount</th>
<th>Installation Factor</th>
<th>Utility Rates</th>
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<td>$7.68/hr (avg)</td>
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*Minimum Sustainable Price

Department of Energy
Award No. DE-EE-0006935

37
Excluded components account for ~60% of system cost at 1k/year and ~30% at 100k/year

Excluded items (primarily balance of system) cost reductions are due to favorable economies of scale

The pressure vessel system cost is driven by carbon fiber cost which does not show economies of scale as favorable as balance of system
• Components selected for study represent 60% and 46% of the stack cost at 1k/year and 100k/year, respectively.
• Study focused on the four components which define the cell (bipolar plates, membrane, catalyst, and GDL)