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

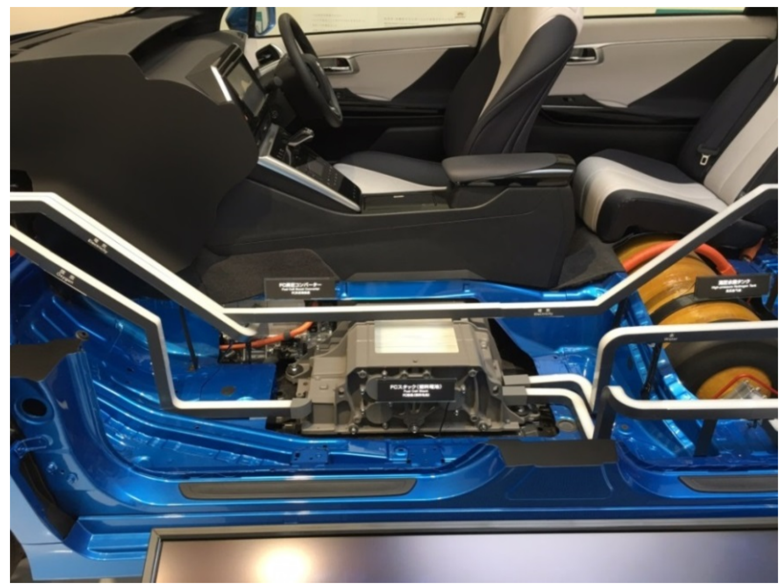

Photo of Mirai by Patrick Fullenkamp

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Department of Energy
Award No. DE-EE-0006935

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

Approach

Clean Energy Supply Chain and Manufacturing Competitiveness Analysis for Hydrogen and Fuel Cells

U.S Department of Energy Project DE-EE-0006935

- **Task 1:** Competitiveness Analysis
  - Historic Supply Chain Analysis
  - OEM and Supplier Interviews
  - Cost Analysis
- **Task 2:** International Fuel Cell Trade-Flows

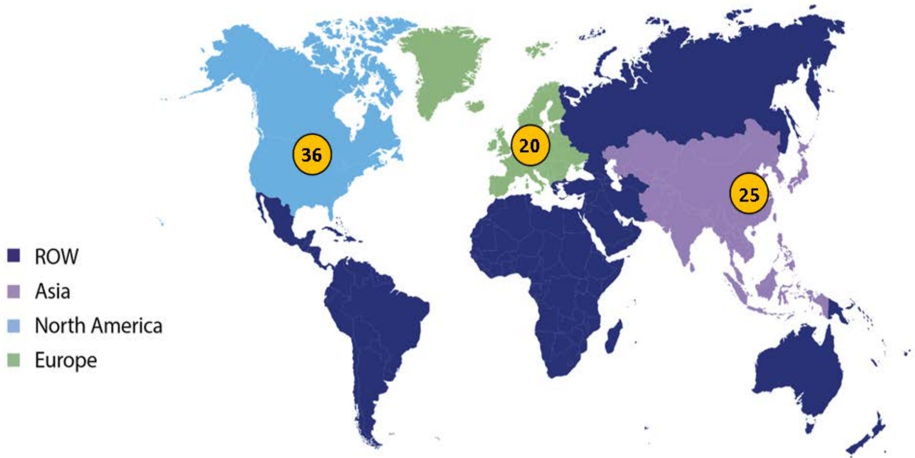
<u>Project Summary</u>: To study the state of hydrogen and fuel cell manufacturing, and to characterize the factors that impact the global competitiveness of fuel cell and hydrogen related manufacturing

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

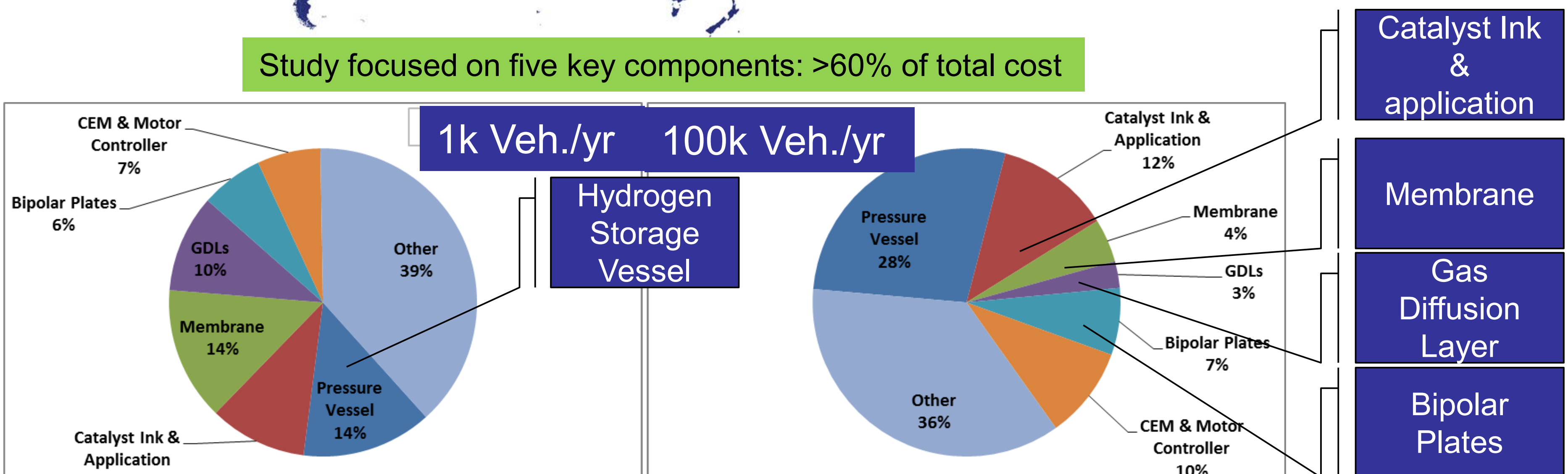
- **Implications for the U.S.**

Approach: Actors by Region; key suppliers; cost breakdowns



COMPONENT	USA	Asia	Europe
Bipolar Plates	2	2	2
Membrane	1	2	1
Gas Diffusion Layer	1*	1	2
Catalyst Ink	1*	1	2
Pressure Vessels	1	1	1

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



Other items included in cost but not studied: **H_2 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, H_2 sensors, coolant & air handling components, fuel system components, humidifier, system controller). See slides 57-58 for further details.

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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

	Bipolar Plate				Catalyst				Gas Diffusion layer				Membrane				H2 Vessel			
	US	EU	Asia		US	EU	Asia		US	EU	Asia		US	EU	Asia		US	EU	Asia	
			Japan	China			Japan	China			Japan	China			Japan	China			Japan	China
1-10k	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH
100k	M-L	MOD	MOD	LOW	MOD	H-M	H-M	MOD	MOD	MOD	MOD	LOW	H-M	H-M	H-M	H-M	H-M	H-M	H-M	H-M

Manufacturing Readiness

	Bipolar Plate				Catalyst				Gas Diffusion layer				Membrane				H2 Vessel			
	US	EU	Asia		US	EU	Asia		US	EU	Asia		US	EU	Asia		US	EU	Asia	
			Japan	China			Japan	China			Japan	China			Japan	China			Japan	China
1-10k	H-M	HIGH	HIGH	HIGH	H-M	HIGH	HIGH	HIGH	H-M	HIGH	HIGH	HIGH	H-M	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH
100k	M-L	MOD	MOD	LOW	MOD	H-M	H-M	LOW	M-L	MOD	MOD	LOW	LOW	MOD	M-L	LOW	M-L	M-L	M-L	M-L

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>
<tr><th></th><th colspan="2">BPP</th><th colspan="2">Membrane</th><th colspan="2">Catalyst</th><th colspan="2">GDL</th><th colspan="2">Vessel</th></tr>
<tr><th></th><th>Near</th><th>Far</th><th>Near</th><th>Far</th><th>Near</th><th>Far</th><th>Near</th><th>Far</th><th>Near</th><th>Far</th></tr>
<tr><td rowspan="6">Manuf. Potential</td><td rowspan="2">Forming Low</td><td rowspan="2">Forming High</td><td rowspan="2">Ionomer Low</td><td rowspan="2">Ionomer Mod</td><td rowspan="6">Low</td><td rowspan="6">Mod-Low</td><td rowspan="6">Mod</td><td rowspan="6">Mod</td><td rowspan="3">Fiber High-Mod</td><td rowspan="3">Fiber High-Mod</td></tr>
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<tr><td rowspan="2">Coating Mod-Low</td><td rowspan="2">Coating High</td><td rowspan="2">Support Mod</td><td rowspan="2">Support Mod</td></tr>
<tr><td rowspan="3">Fabricate High</td><td rowspan="3">Fabricate High</td></tr>
<tr><td rowspan="2">Joining Low</td><td rowspan="2">Joining High</td><td rowspan="2">R2R High-Mod</td><td rowspan="2">R2R High-Mod</td></tr>
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<tr><td rowspan="6">Innov. Potential</td><td rowspan="2">Forming Low</td><td rowspan="2">Forming High</td><td rowspan="2">Ionomer High-Mod</td><td rowspan="2">Ionomer High-Mod</td><td rowspan="6">Mod</td><td rowspan="6">Mod</td><td rowspan="6">Mod</td><td rowspan="6">Mod</td><td rowspan="3">Fiber High-Mod</td><td rowspan="3">Fiber High-Mod</td></tr>
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Manufacturing Potential

<table>
<tr><td>HIGH</td><td rowspan="5">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.</td></tr>
<tr><td>HIGH TO MODERATE</td></tr>
<tr><td>MODERATE</td></tr>
<tr><td>MODERATE TO LOW</td></tr>
<tr><td>LOW</td></tr>
</table>

Innovation Potential

<table>
<tr><td>HIGH</td><td rowspan="5">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.</td></tr>
<tr><td>HIGH TO MODERATE</td></tr>
<tr><td>MODERATE</td></tr>
<tr><td>MODERATE TO LOW</td></tr>
<tr><td>LOW</td></tr>
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Accomplishments: HFC Jobs & Investment at 100k vehicles (stacks & PV's) / year

	Direct LaborJobs	Investment	Units / year
Bipolar Plate (BPP)	30 - 40	\$80M Capex \$36M Facilities	37M
Catalyst	20 - 40	\$2.4M Capex \$14M Facilities	1,800kg Pt
Gas Diffusion Layer (GDL)	35 - 50	\$30M Capex \$13M Facilities	2.4M m^2
Membrane	35 – 50	\$7M Capex \$5M Facilities	2.4M m^2
Pressure Vessel (PV)	160 – 190	\$33M Capex \$74M Facilities	100,000

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:

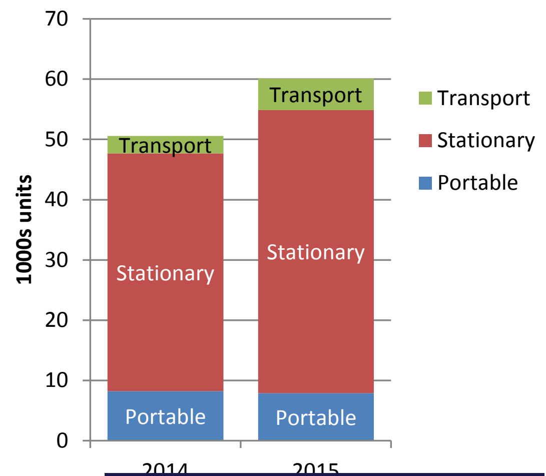
- **Growth in Asia is much faster. Demand will increasingly be met by Asian suppliers, who then will out-compete U.S. suppliers.**
- **Lack of Coordinated Incentives/Facilitation**
- **High Corporate tax rate**
- **Increasing R&D Investments outside the U.S.**

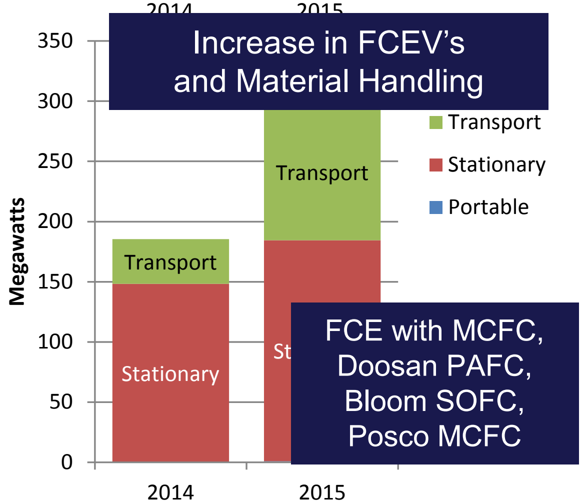
Options include:

- **Further demand-side support to help 'pull through' supplier base**
- **Support for strategic, job creating and high value added manufacturing**

Accomplishments: 2014 – 2015 Fuel Cell Market Data – E4tech (continuing 2016, 2017)

By application

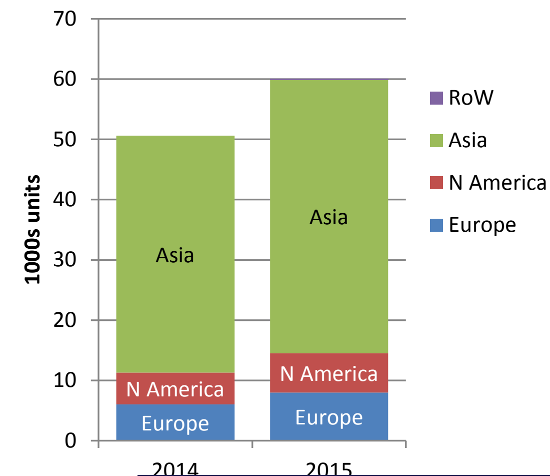


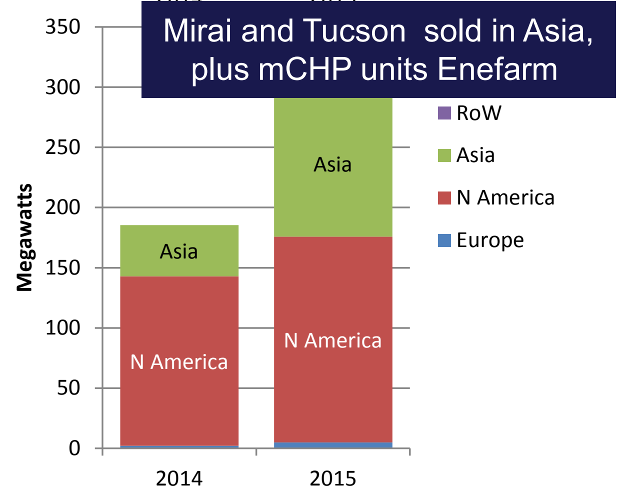


Increase in FCEV's and Material Handling

FCE with MCFC, Doosan PAFC, Bloom SOFC, Posco MCFC

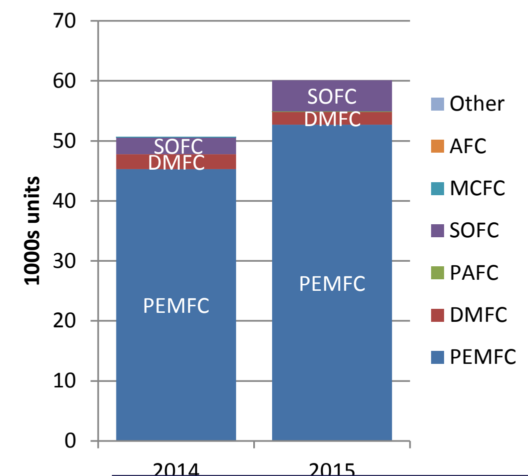
By region of manufacture

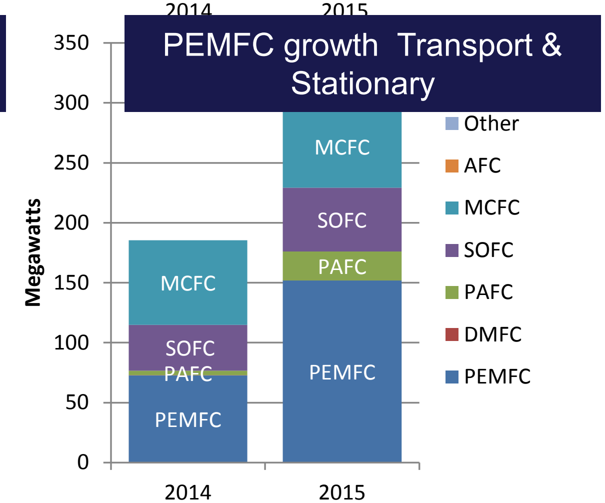




Mirai and Tucson sold in Asia, plus mCHP units Enefarm

By fuel cell technology





PEMFC growth Transport & Stationary

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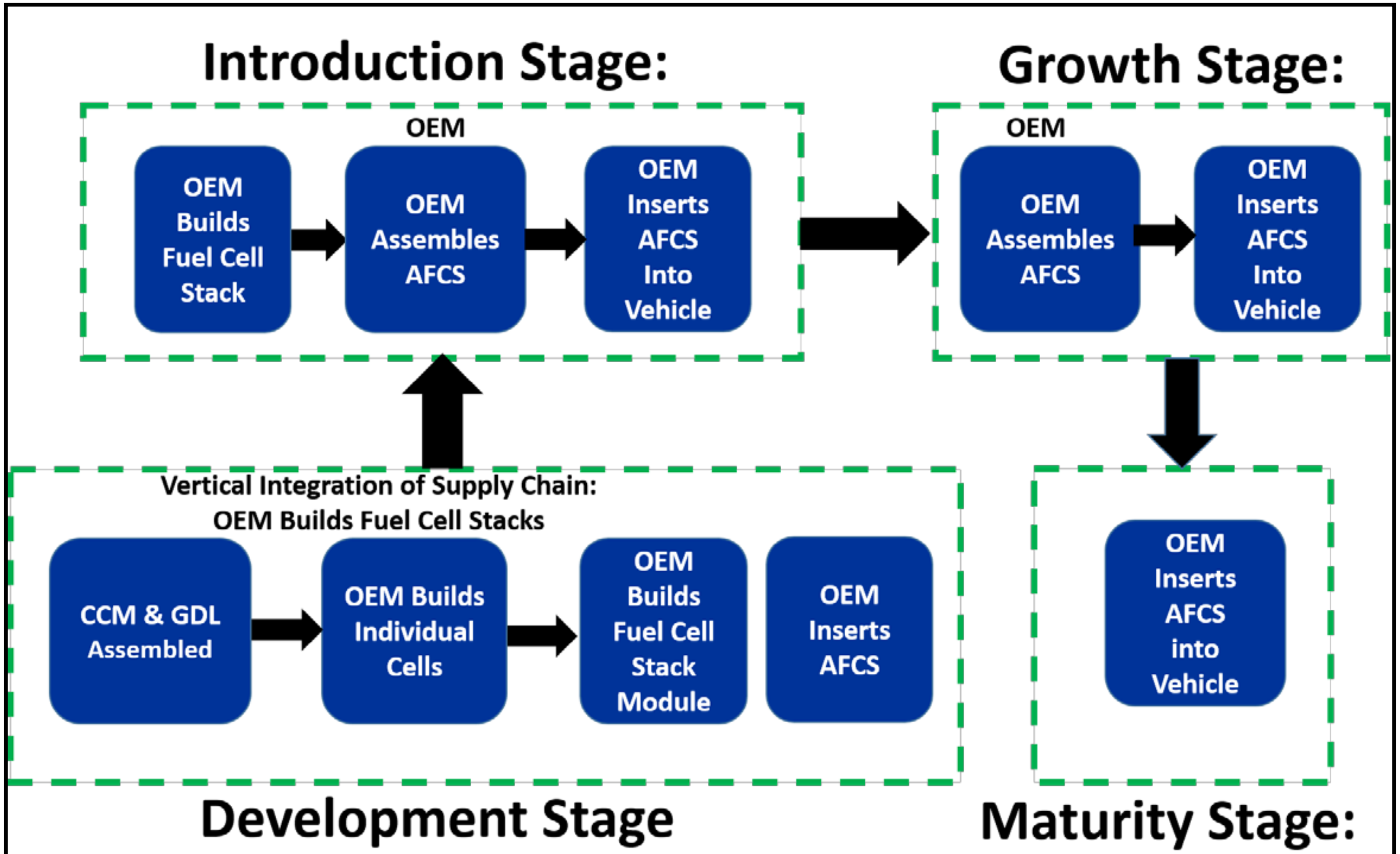
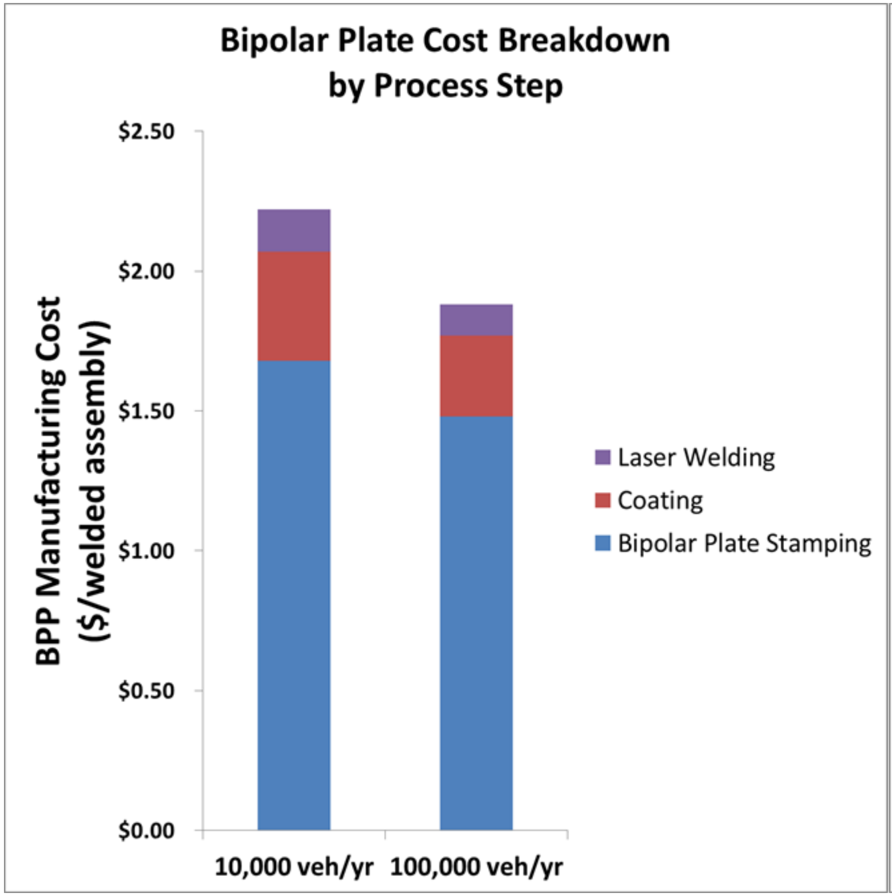
Accomp: Map of one possible OEM transition in responsibility for the production of the AFCS

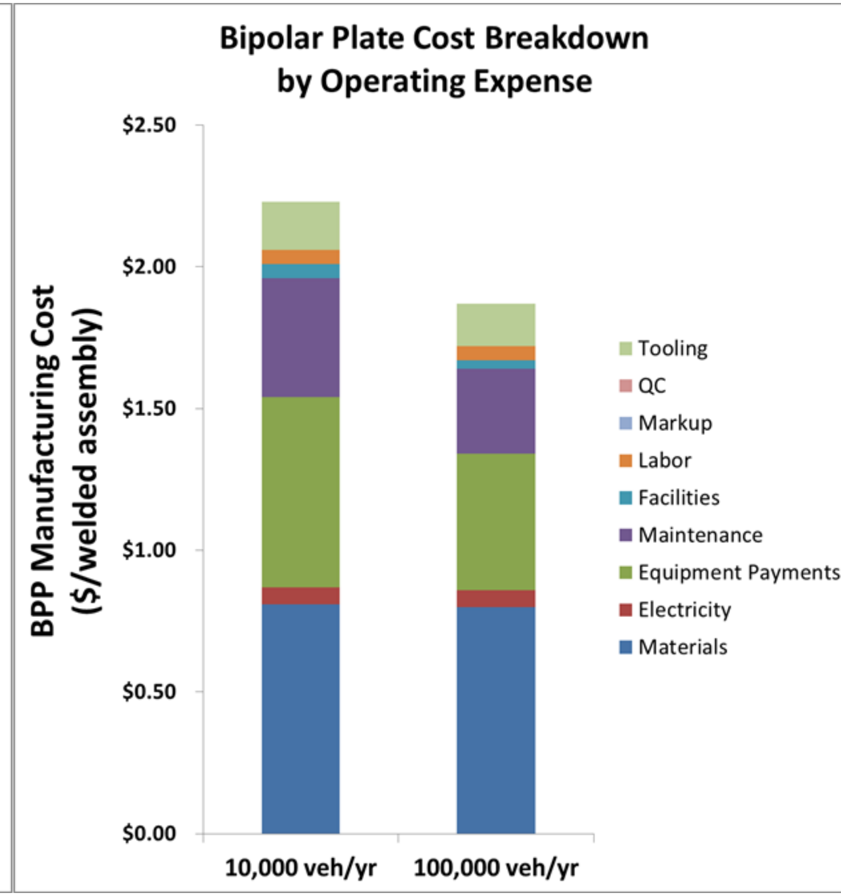


The OEM manufacturing transitions suggested in this slide are consistent with the transitions in the Product-Life-Cycle of an emerging technology; however, the Growth and Maturity stages will be strongly dependent on the manufacturing culture of the different OEMs.

Accomp: Cost breakdown by processing step and operating expense (bipolar plate example)

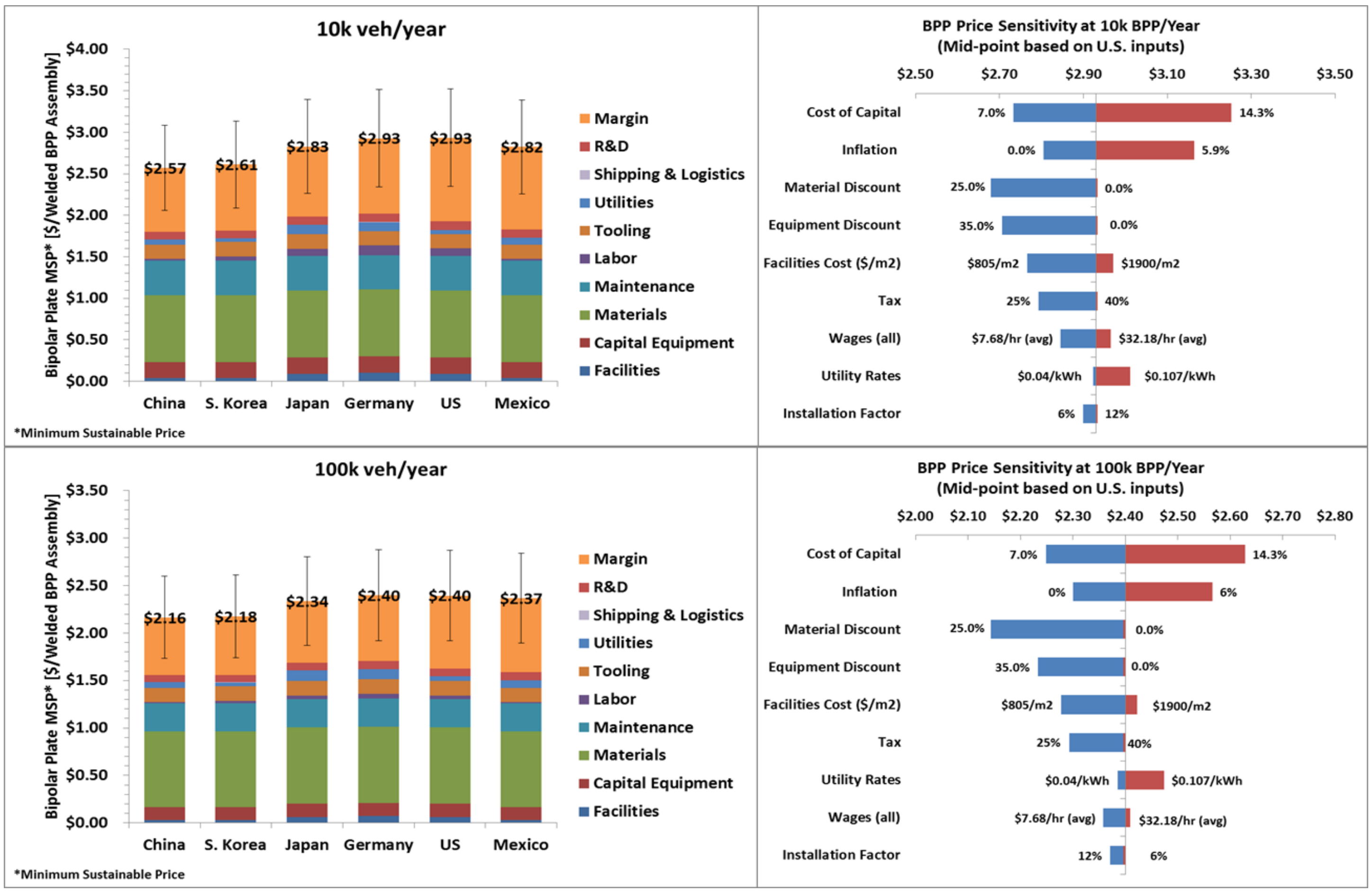
Bipolar plate costs are driven by Capex and stainless steel costs for the stamping operation



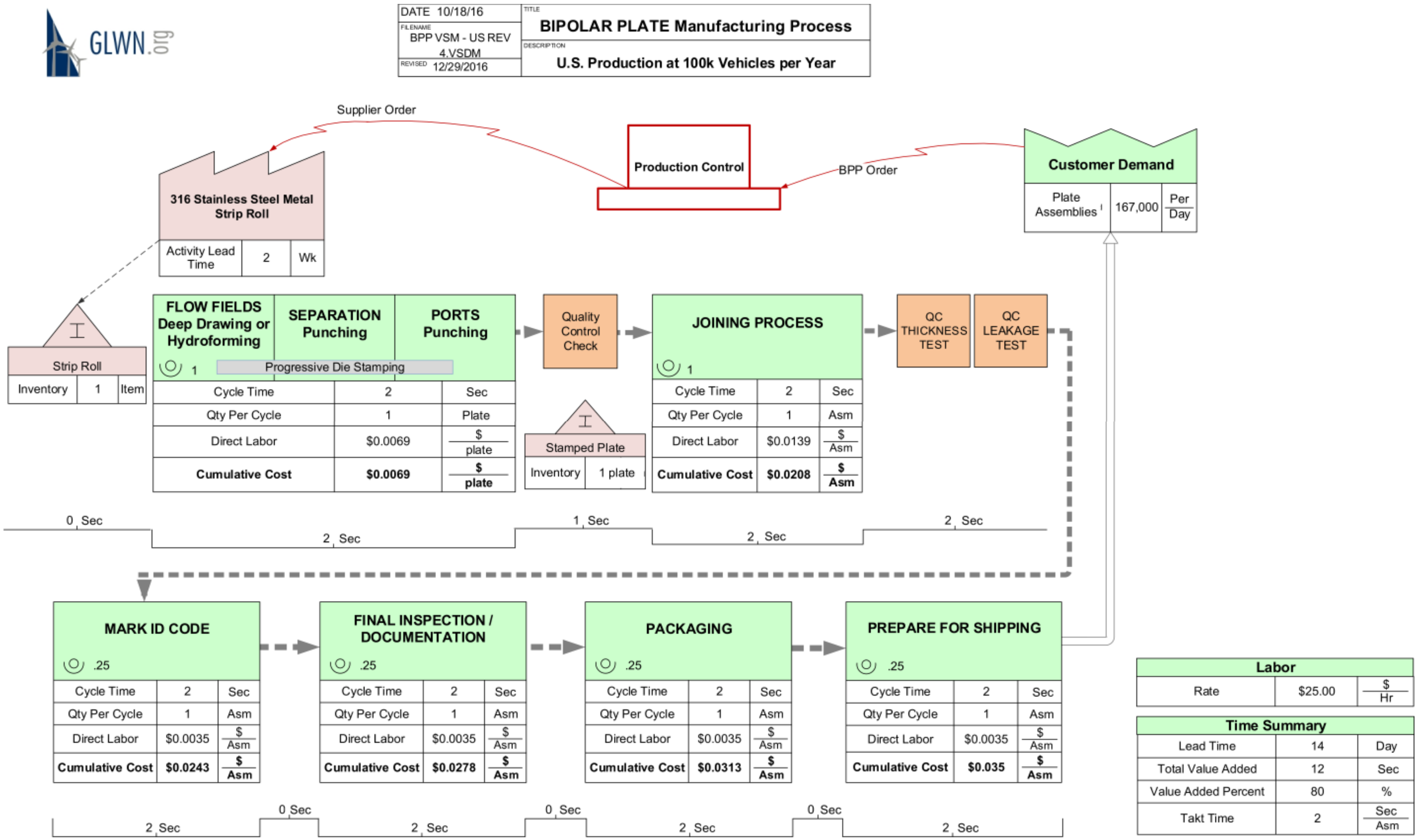


Accomplishments: Discounted Cash Flow Analysis (bipolar plate example)

Access to low-cost stamping equipment (either through low-cost capital or equipment discounts) and materials, and economies are competitive advantages



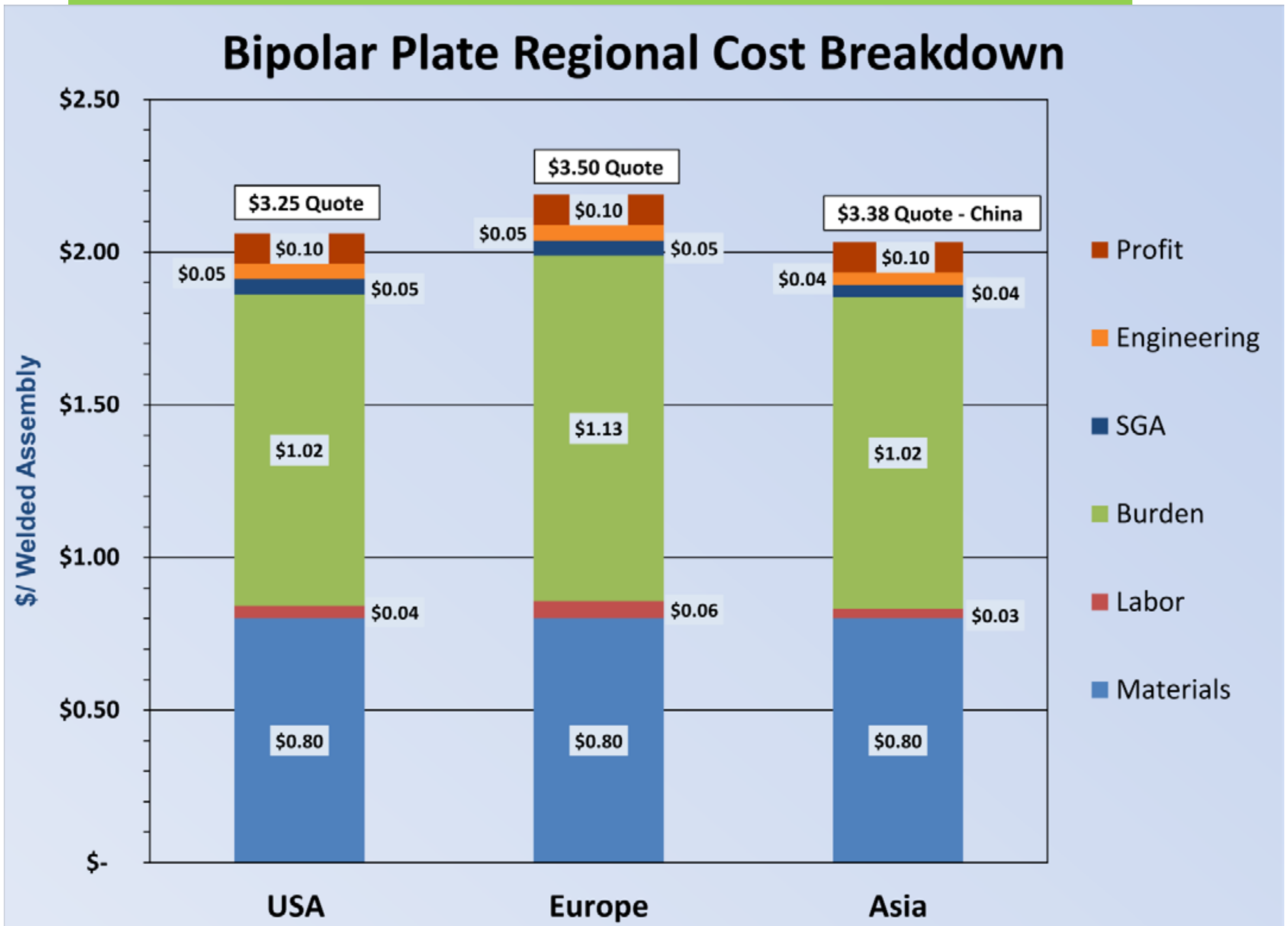
Accomp: Value Stream Map (bipolar plate example)



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

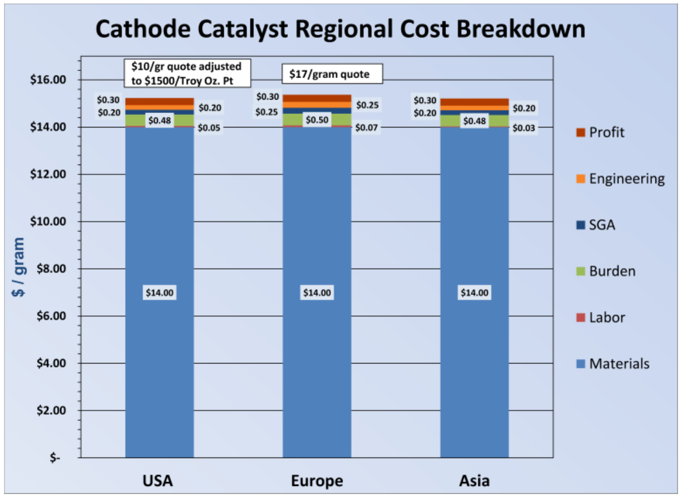
Accomplishments: Regional Cost Breakdown for Bipolar plate

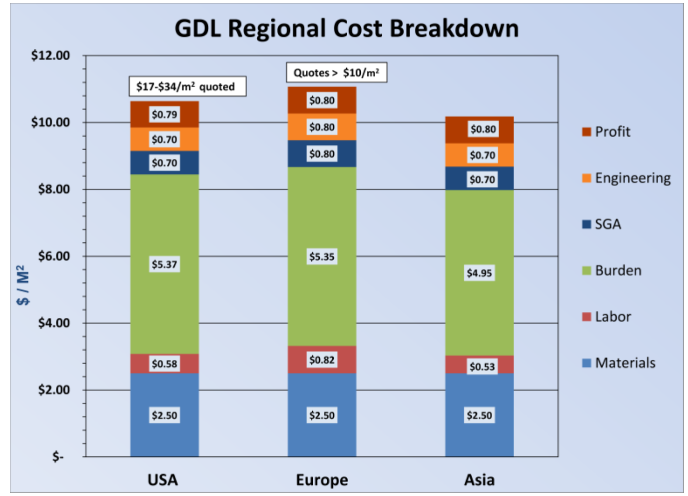
Global stamped commodity, new Capex for presses drives burden

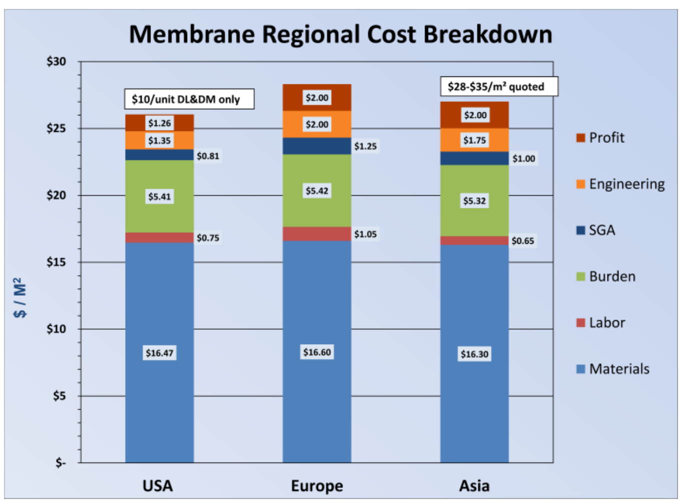


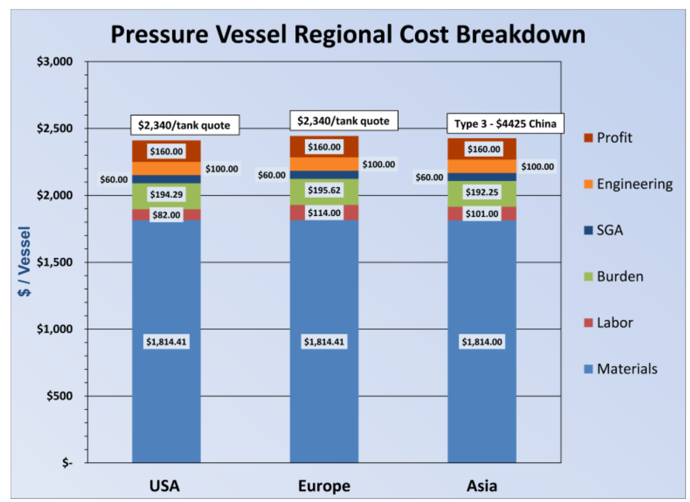
Accomplishments: Regional Cost Breakdown for Catalyst, GDL, Membrane, PV

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









Accomp: Motivations for Developing a Fuel Cell Economy by Country

Big global drivers: Zero polluting emissions (in cities especially), and reduced fleet-wide CO_2 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

Response to Previous Years Reviewers' Comments

"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
- **DOE Fuel Cell Technologies Office, Office of Energy Efficiency and Renewable Energy** – Dr. Nancy Garland, Jesse Adams
- **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 Competitveness 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

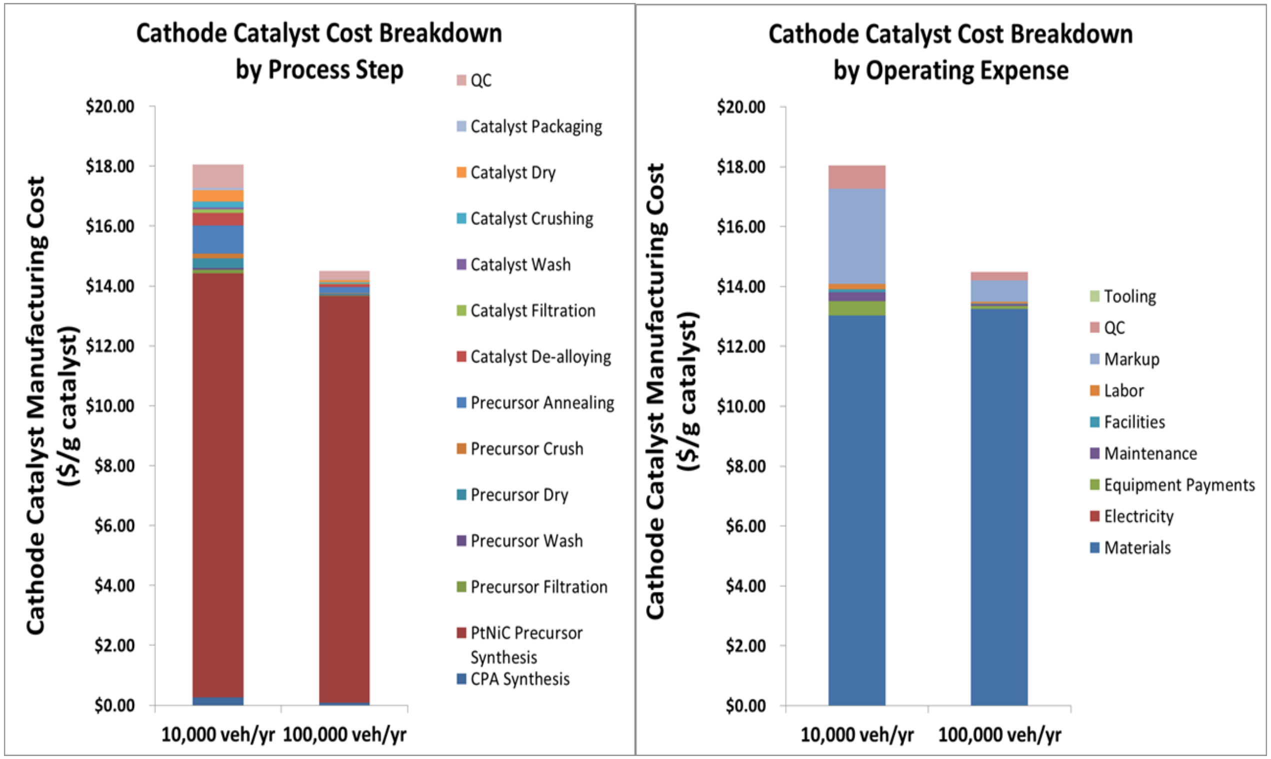
This project has no technology transfer tasks.

Project Summary

- **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 H_2 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 H_2 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 (rt)



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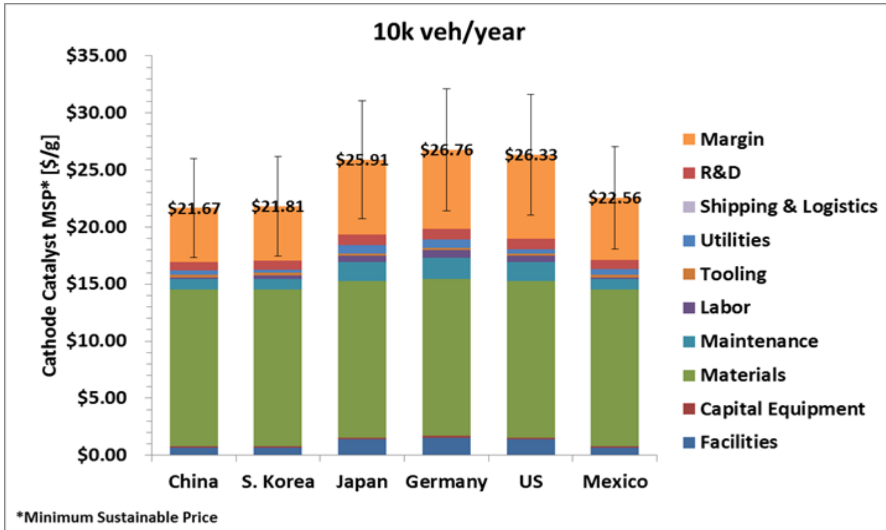
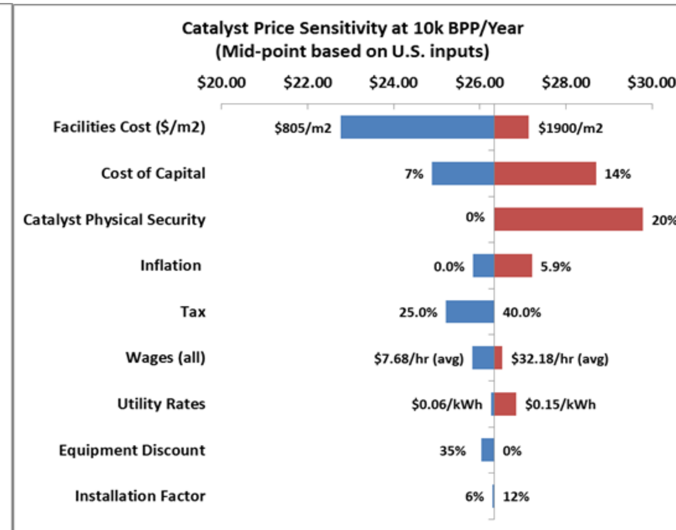
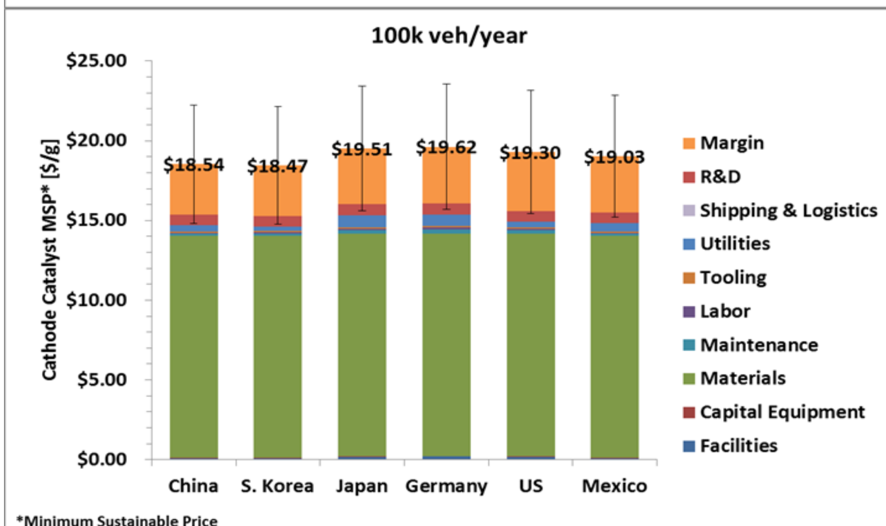
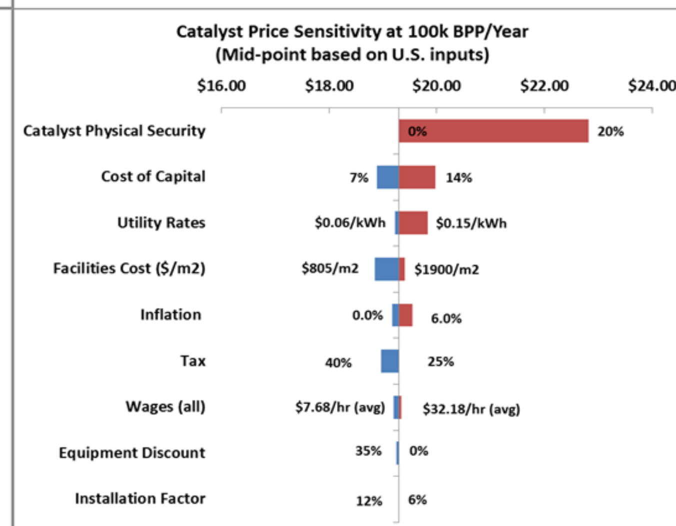
Cathode Catalyst Discounted Cash Flow Analysis

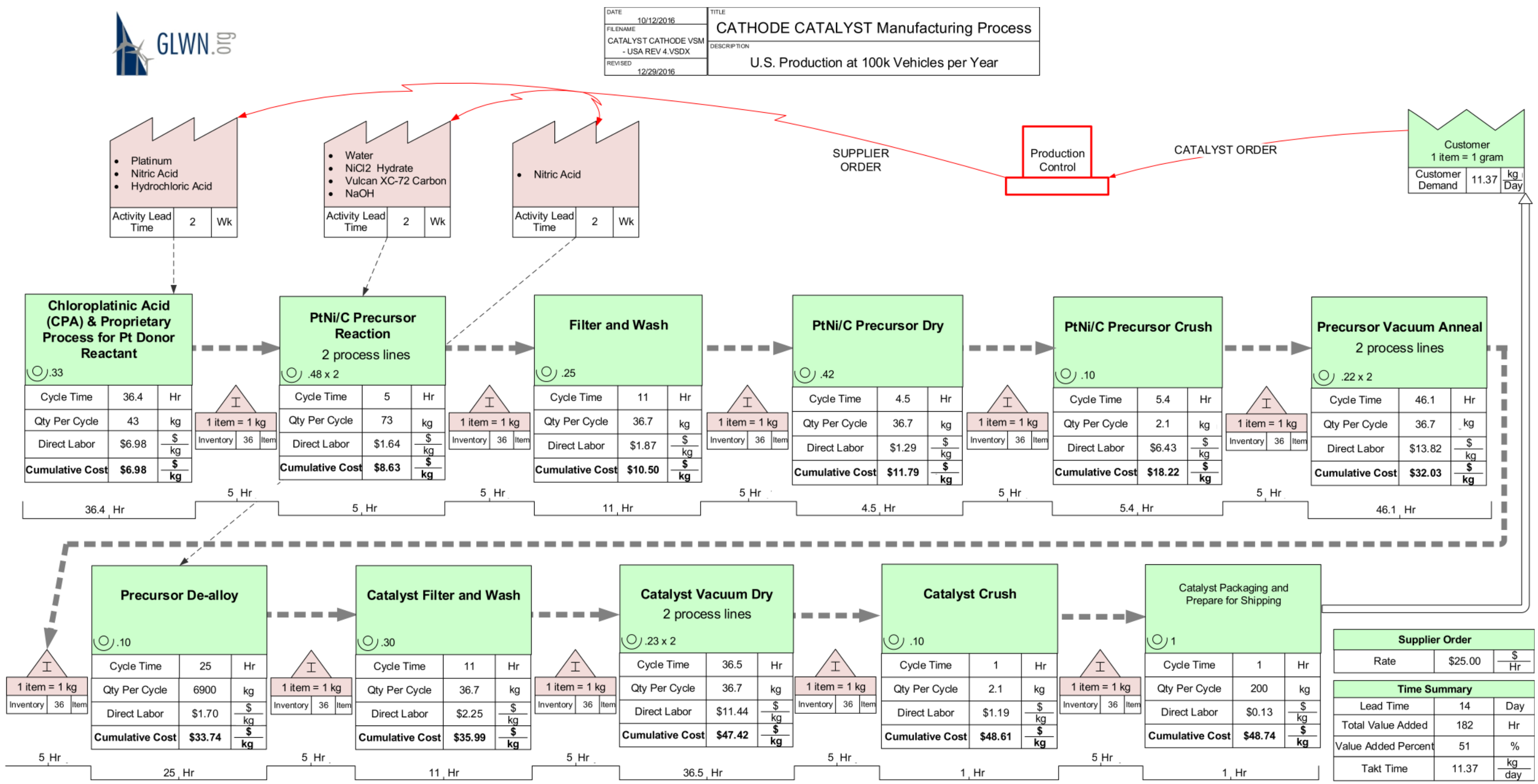








Cathode Catalyst Value Stream Map – U.S.



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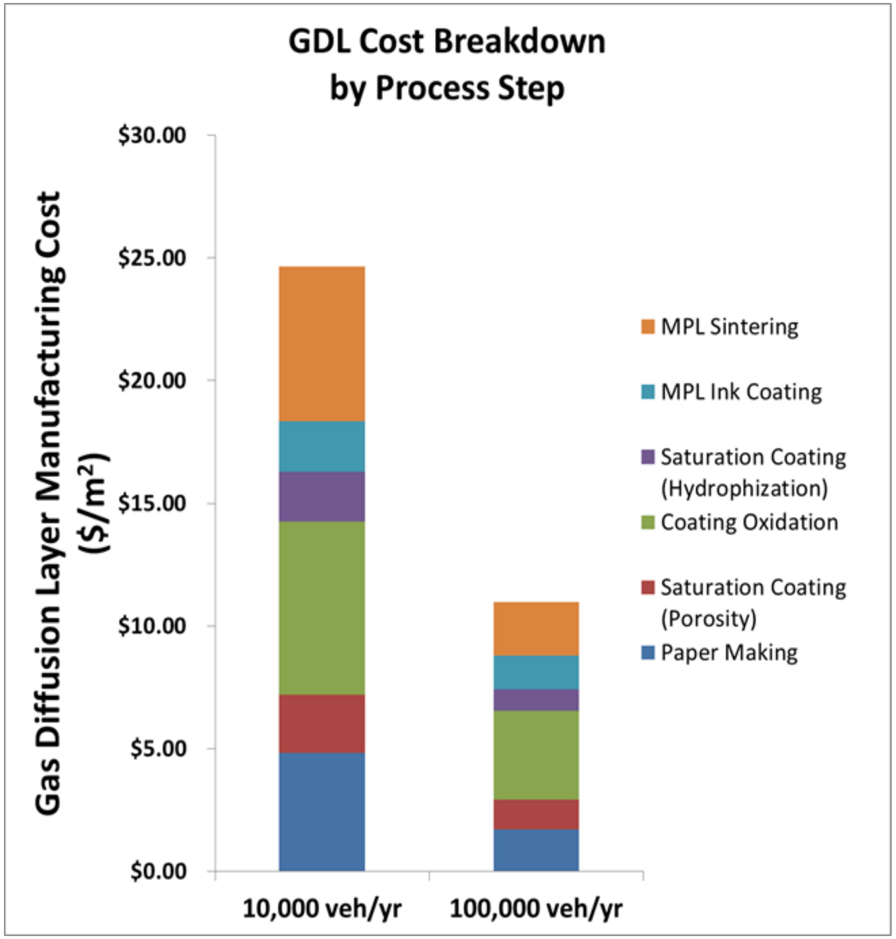
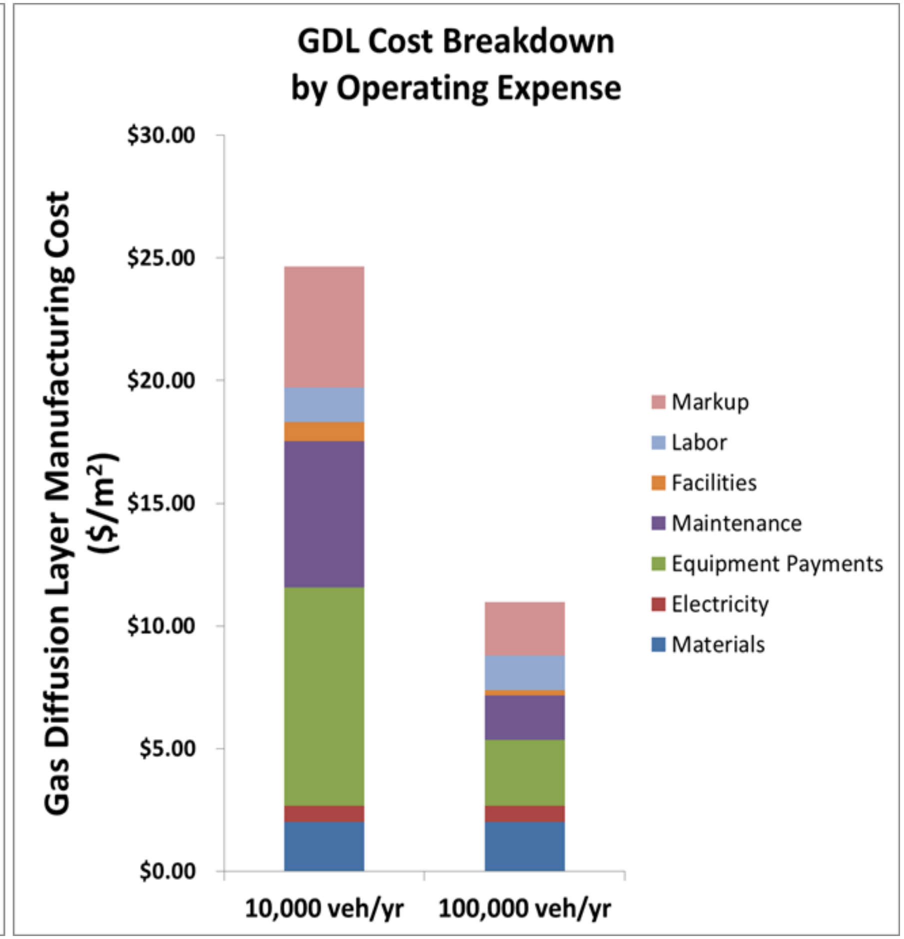
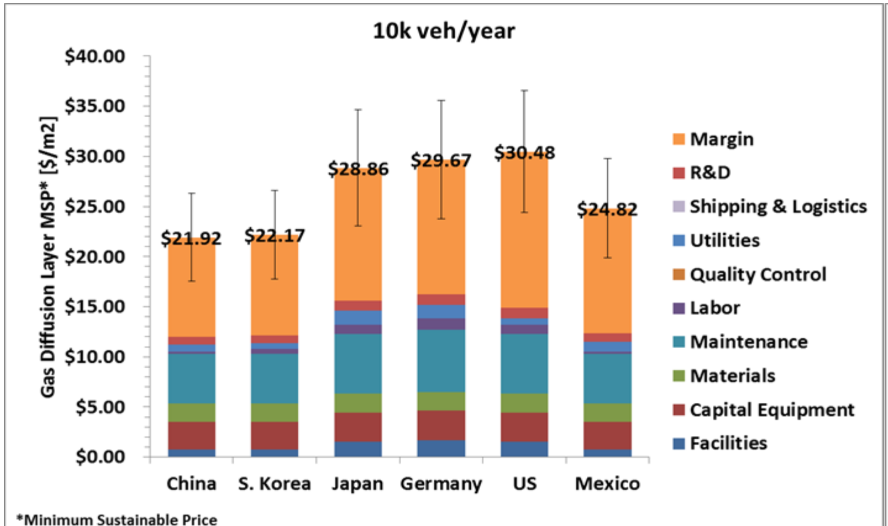
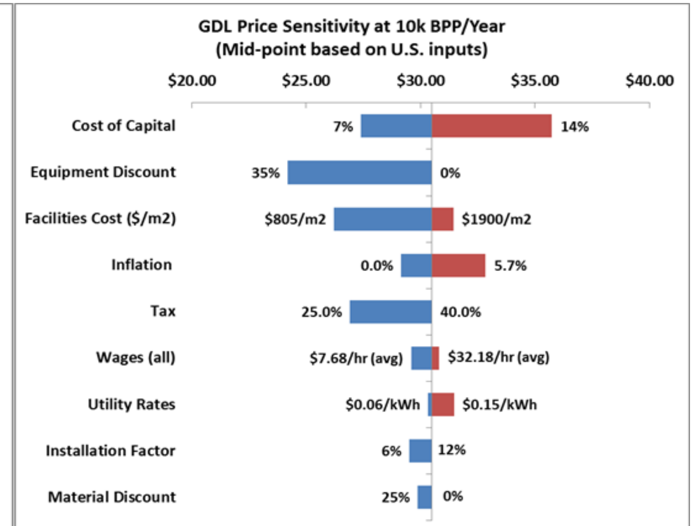
Gas Diffusion Layer cost breakdown by processing step (left) and operating expense (rt)

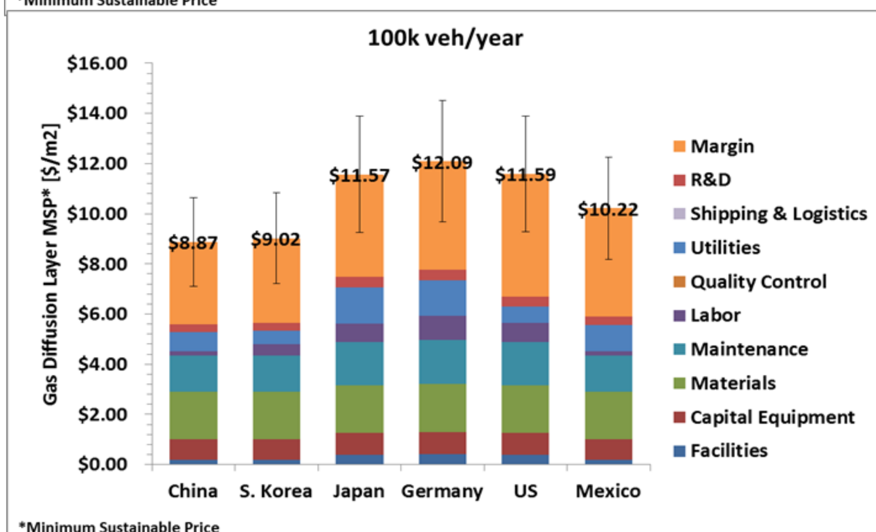


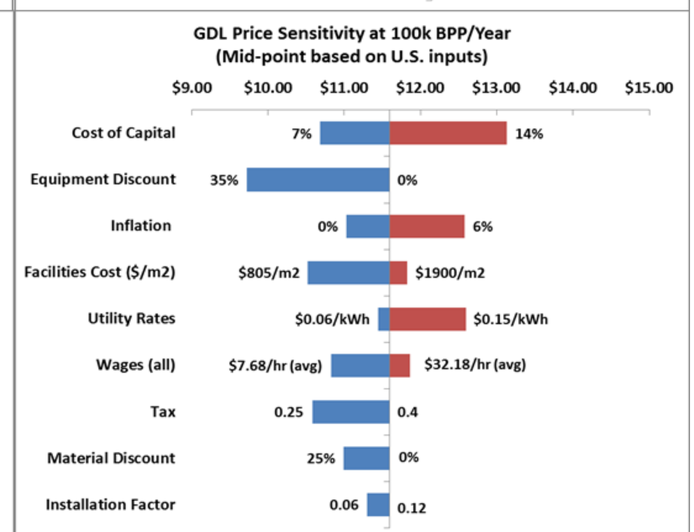


Gas Diffusion Layer Discounted Cash Flow Analysis

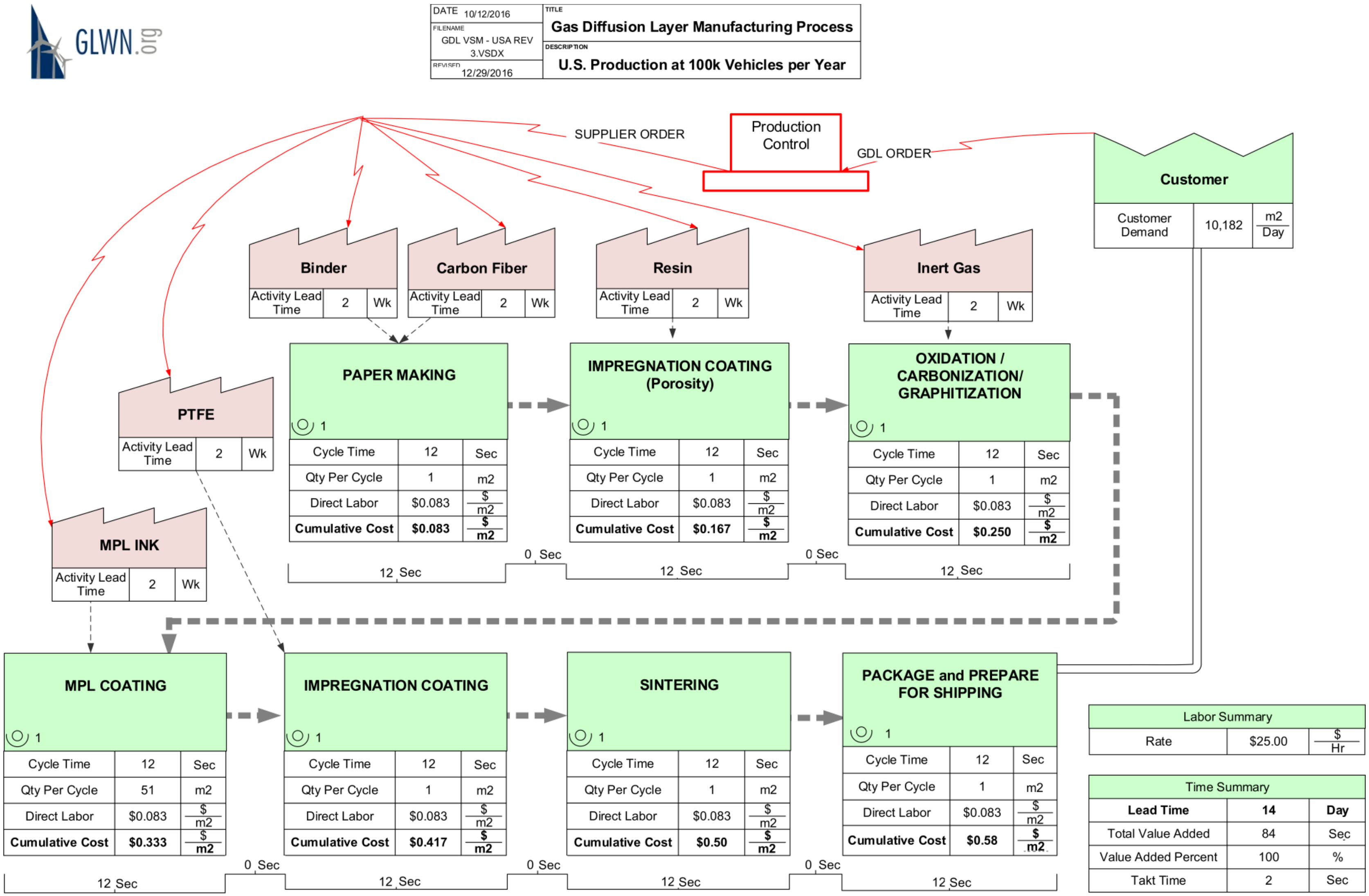




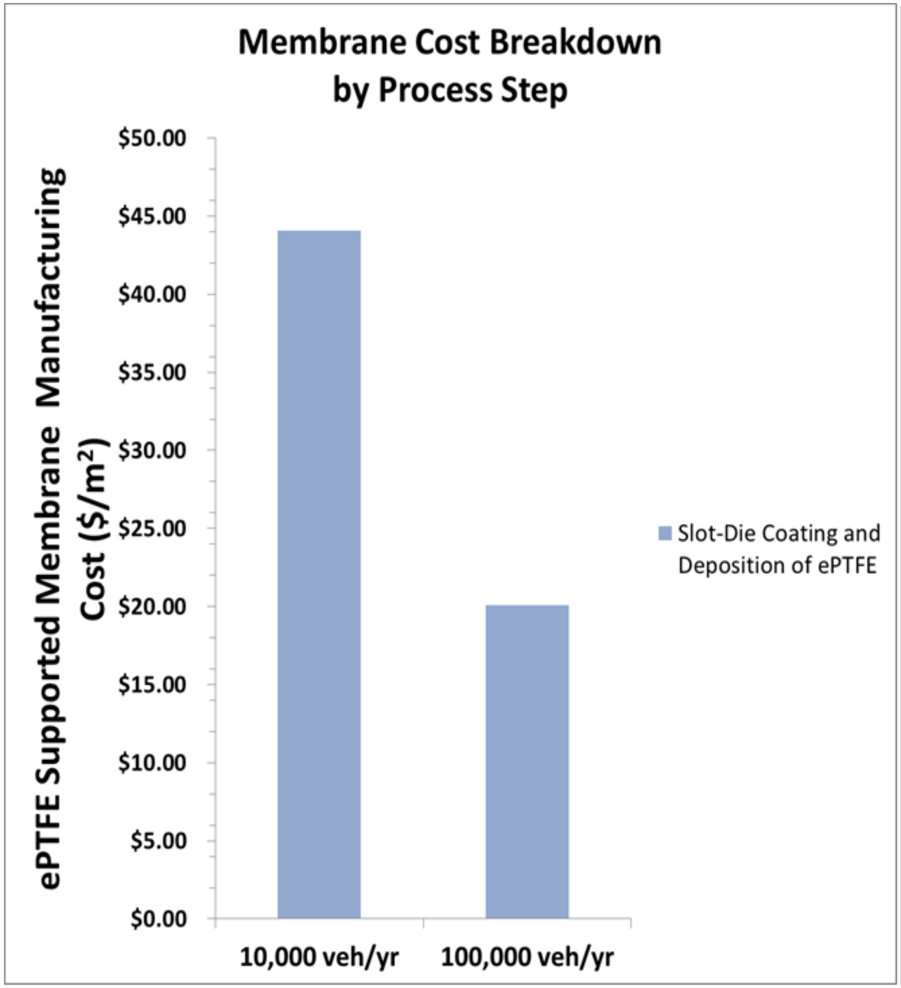


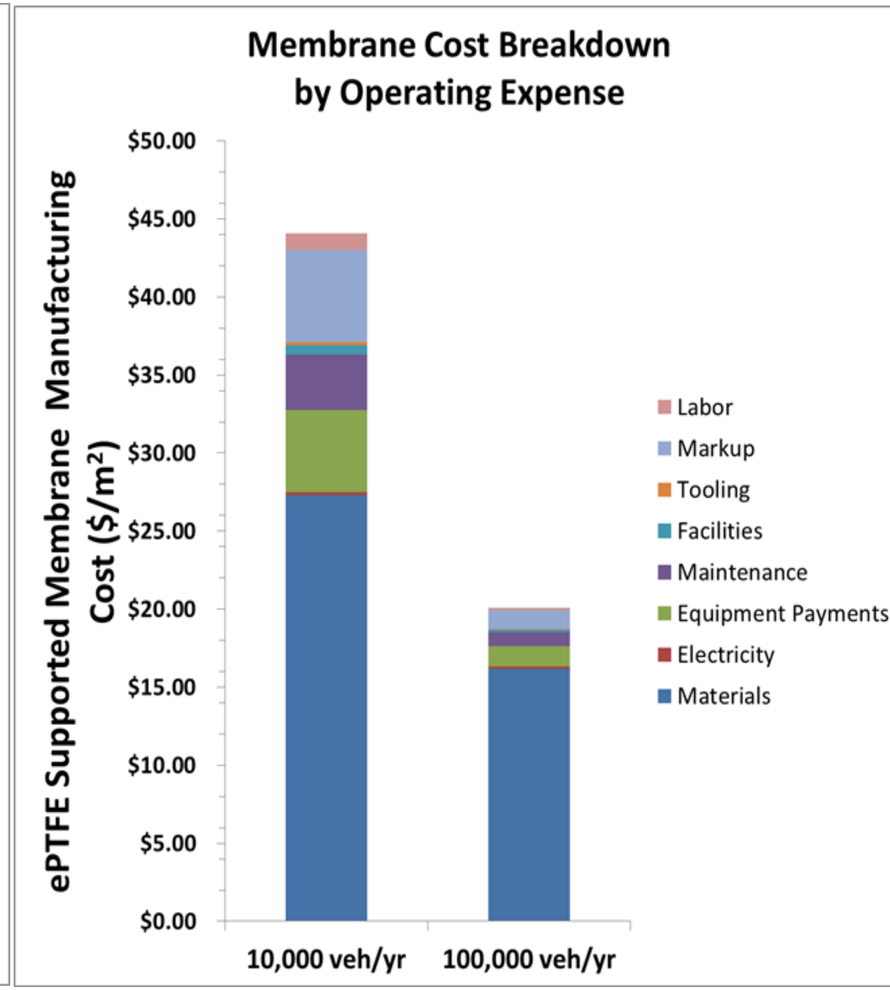


Gas Diffusion Layer Value Stream Map – U.S.

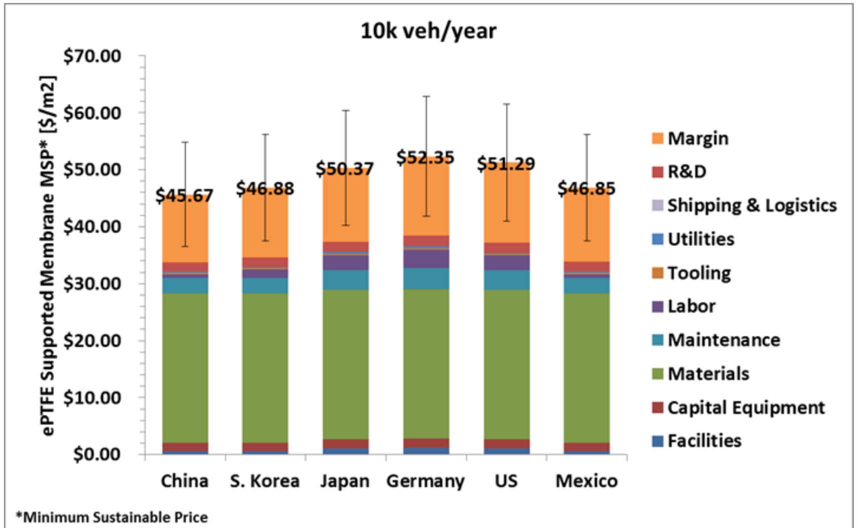


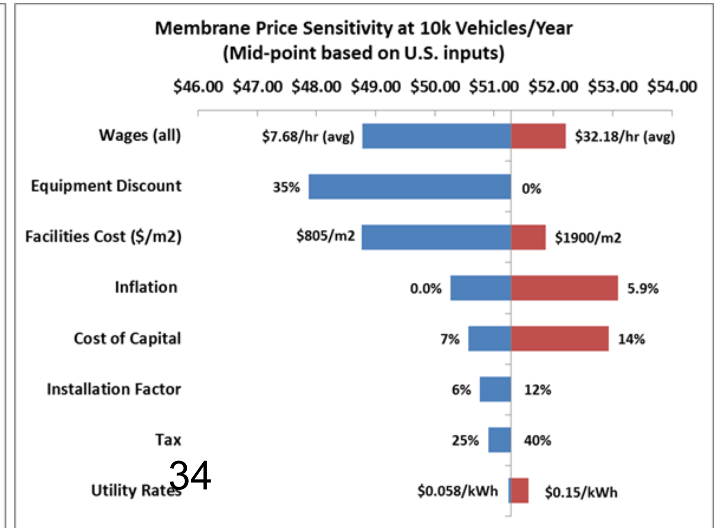
Membrane cost breakdown by processing step (left) and operating expense (rt)

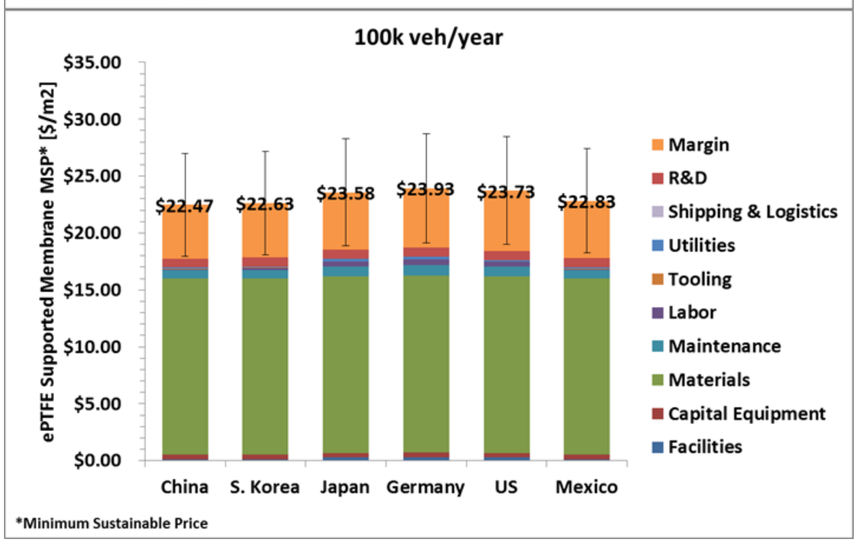


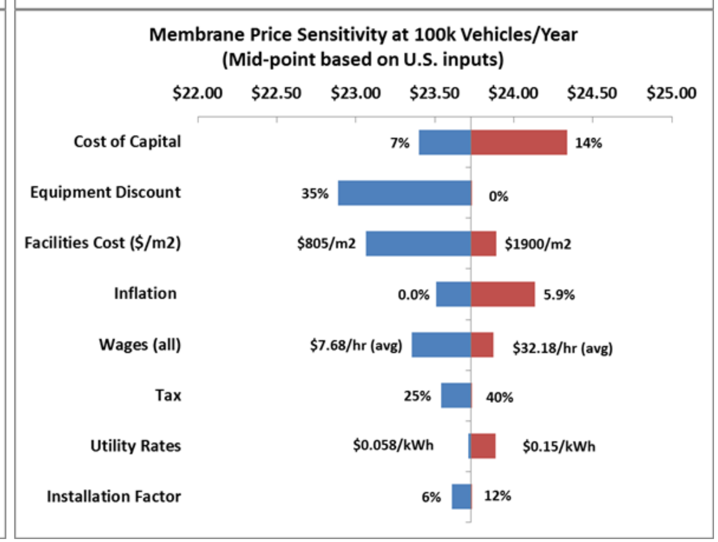


Membrane Discounted Cash Flow Analysis









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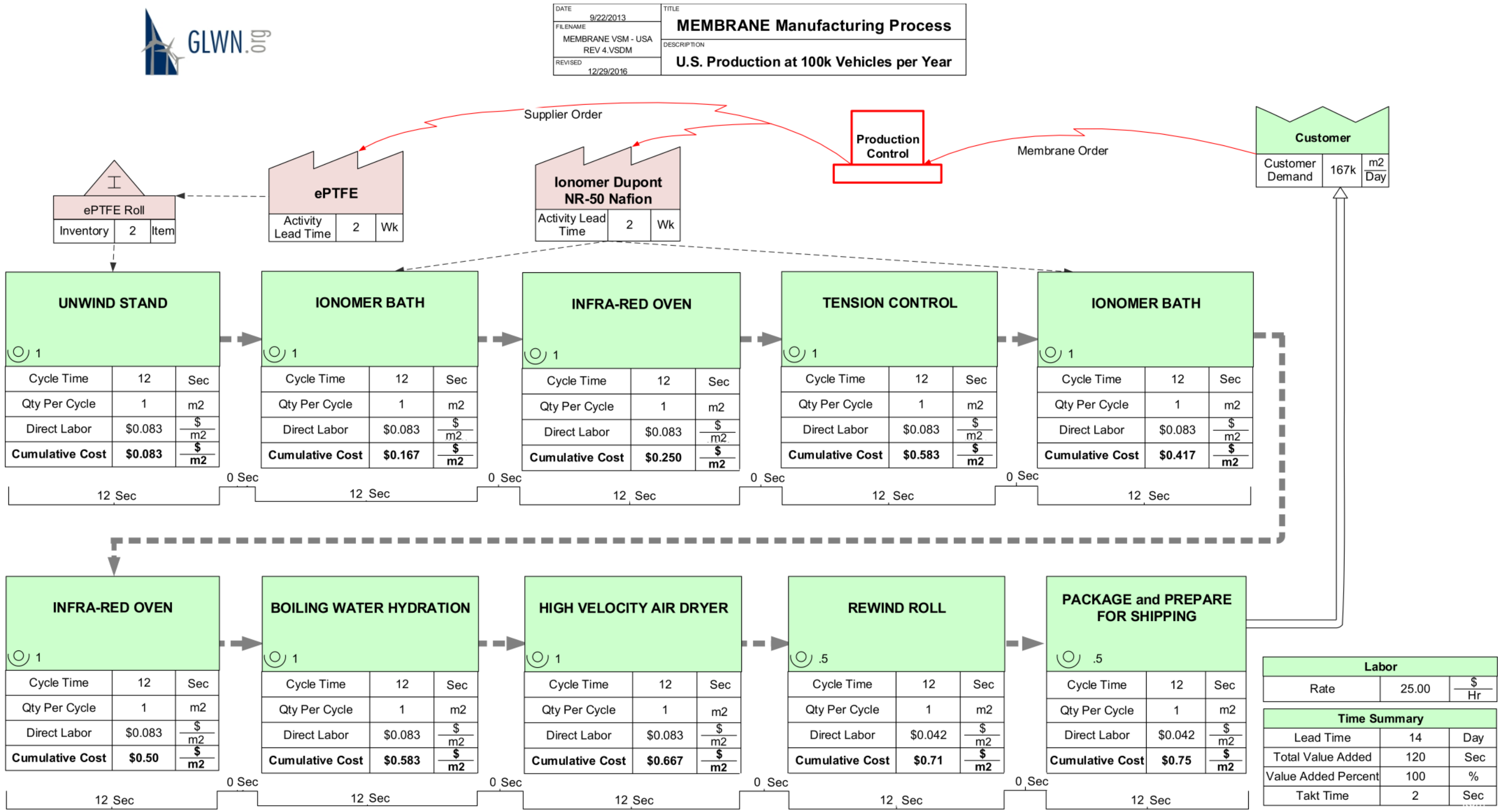
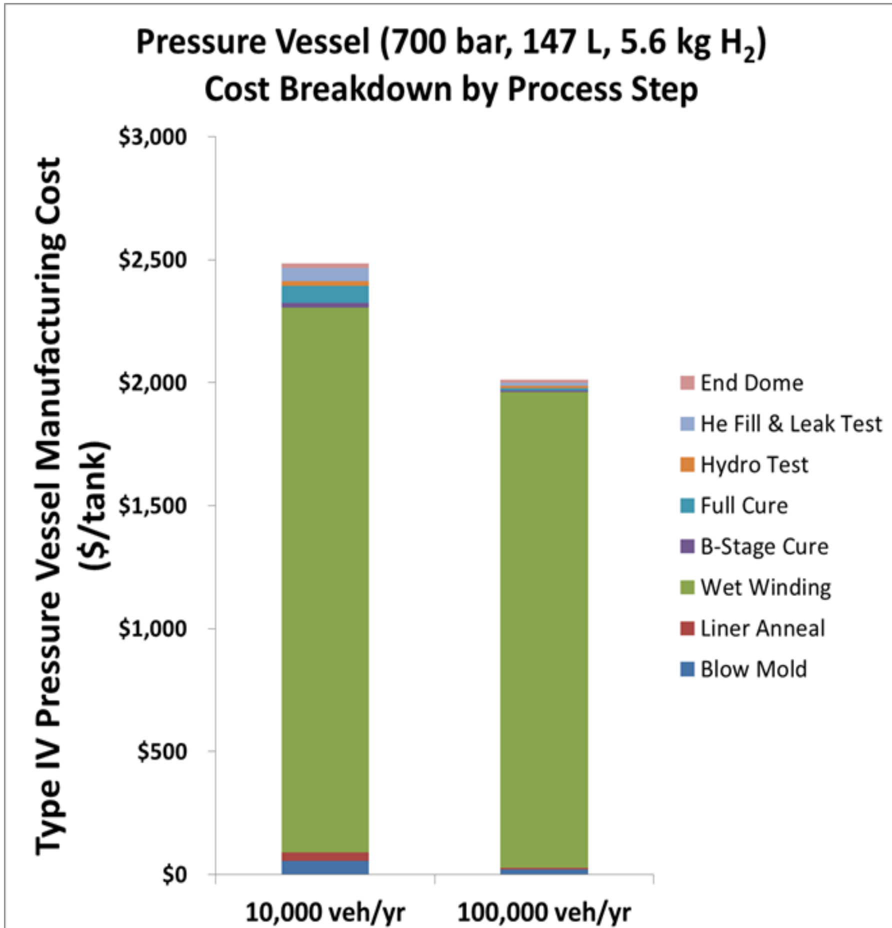
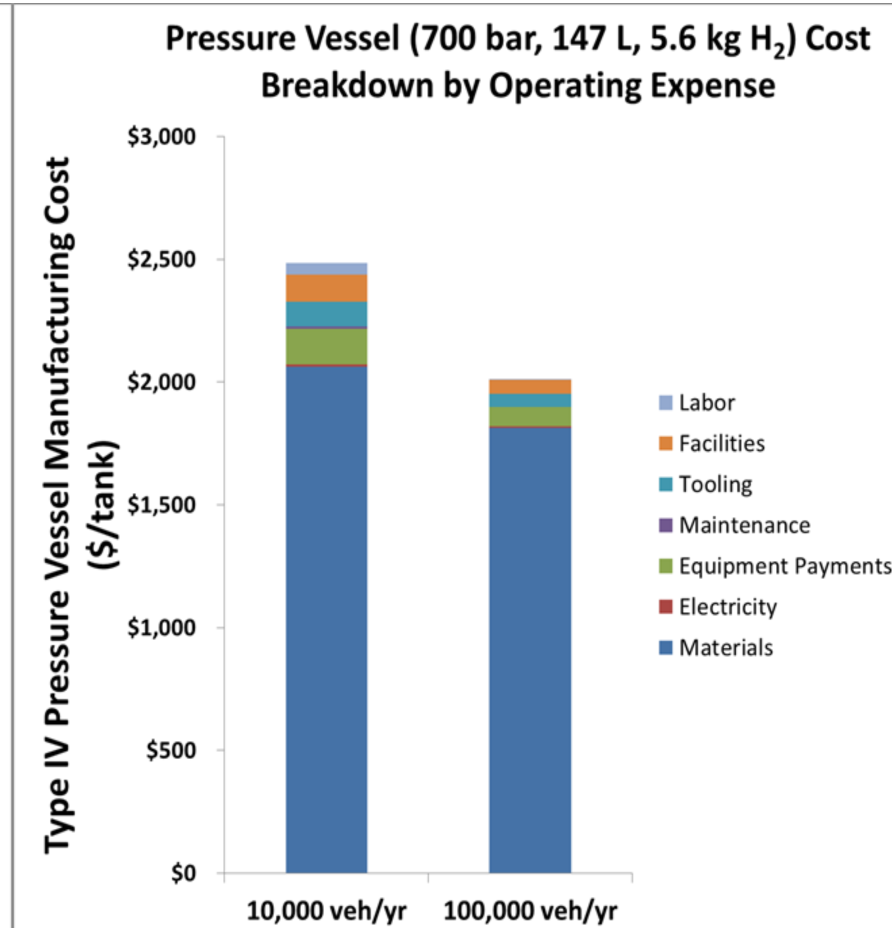
Membrane Value Stream Map – U.S.



Pressure Vessel cost breakdown by processing step (left) and operating expense (rt)





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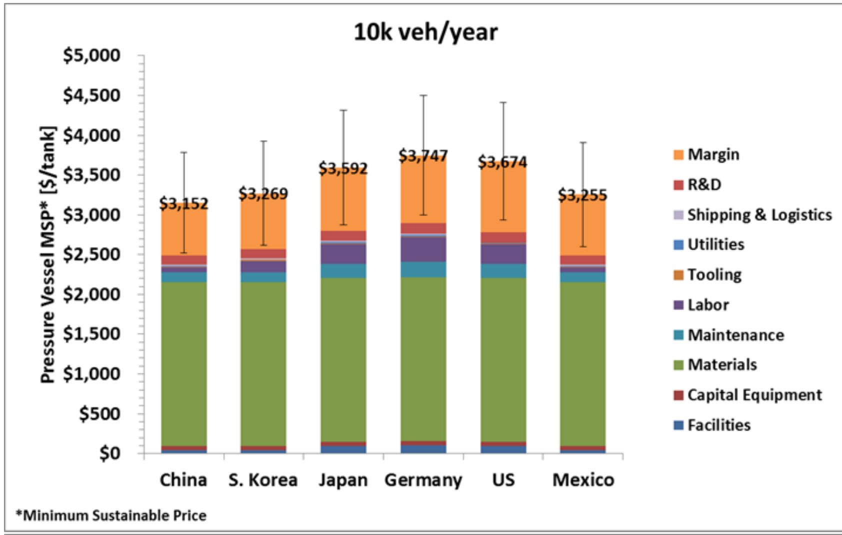
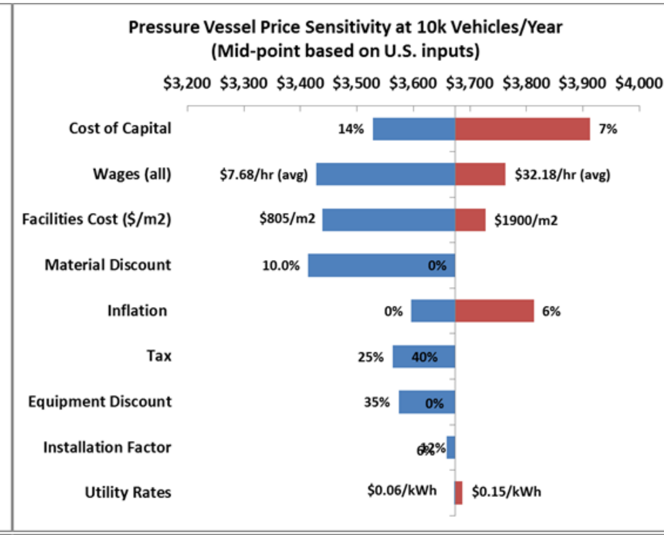
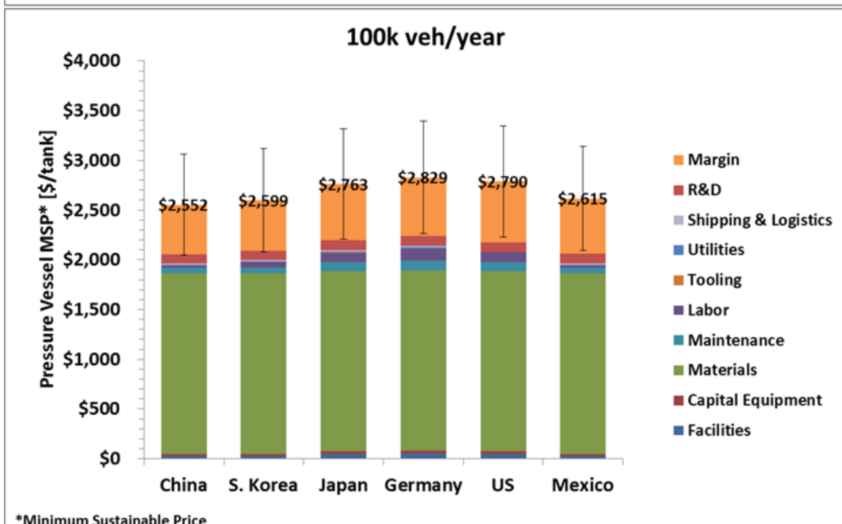
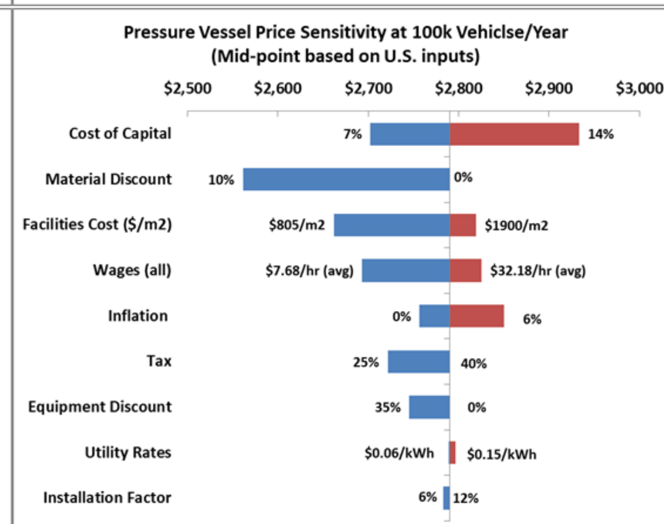
Pressure Vessel Discounted Cash Flow Analysis

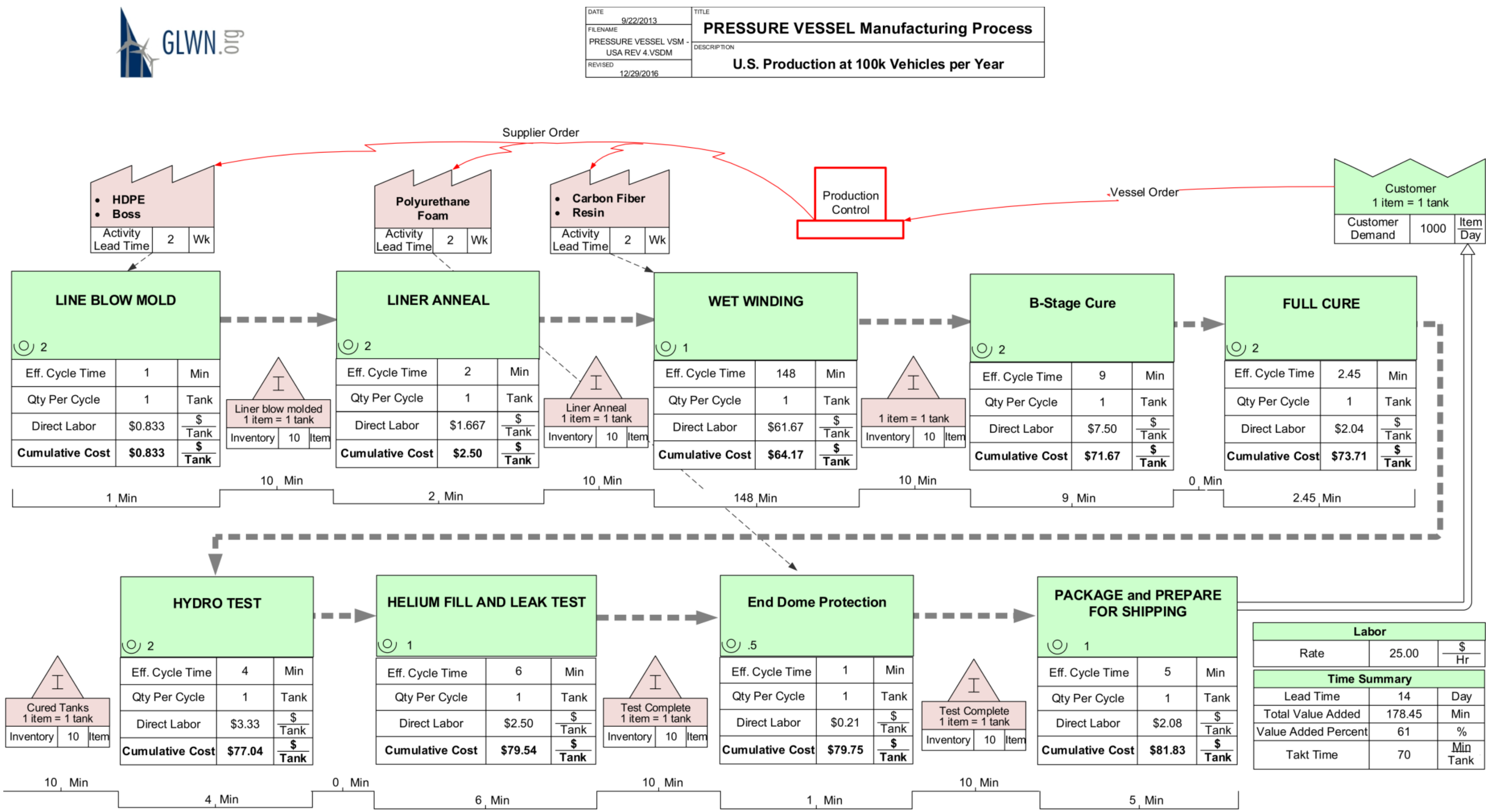






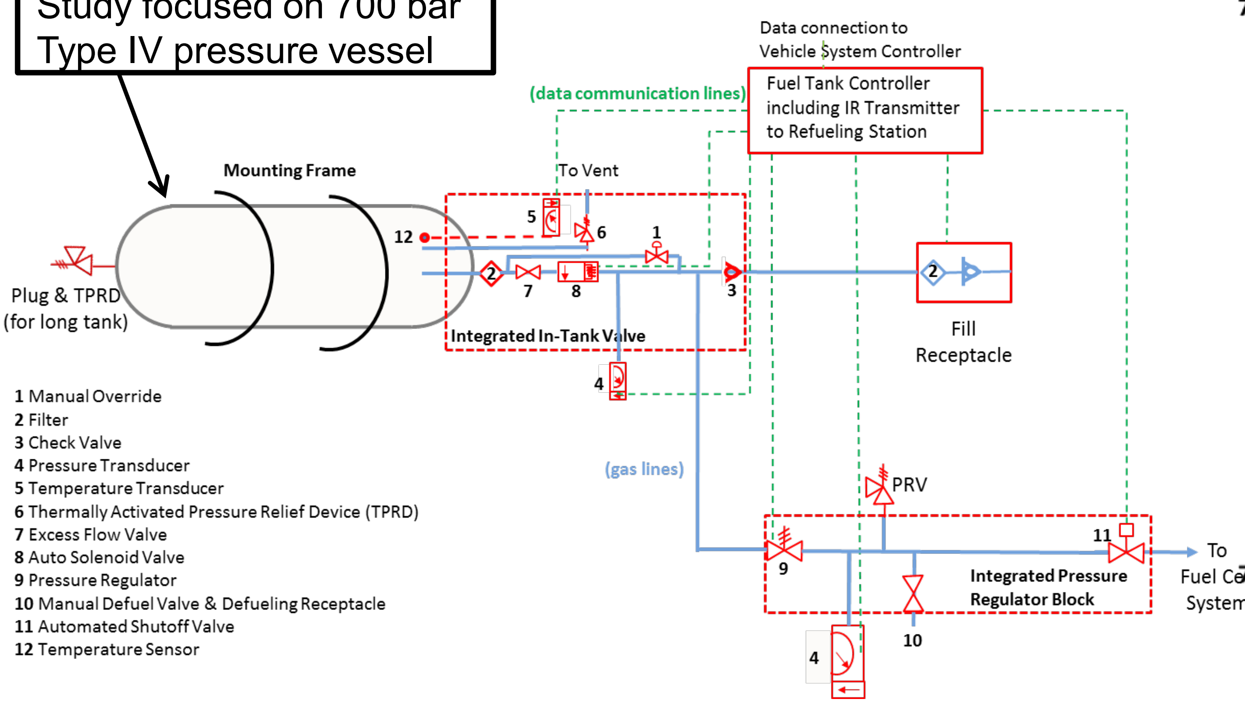


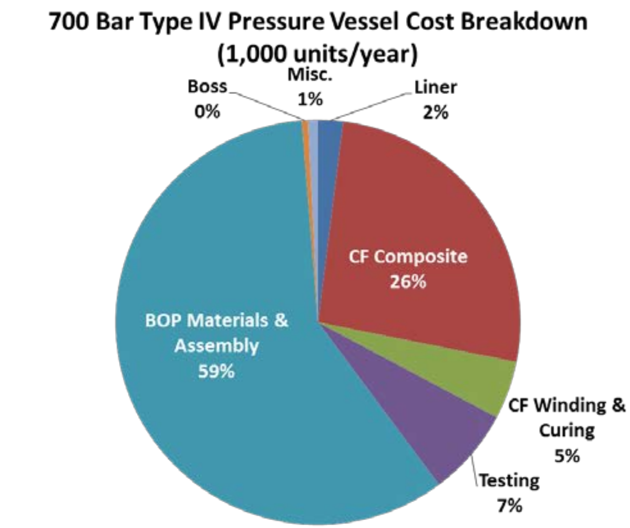
Pressure Value Stream Map – U.S.

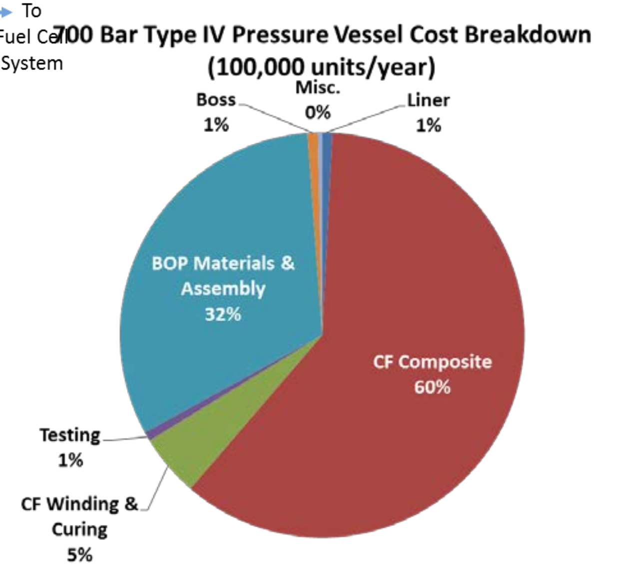


Pressure Vessel Cost Breakdown and System Diagram

Study focused on 700 bar Type IV pressure vessel

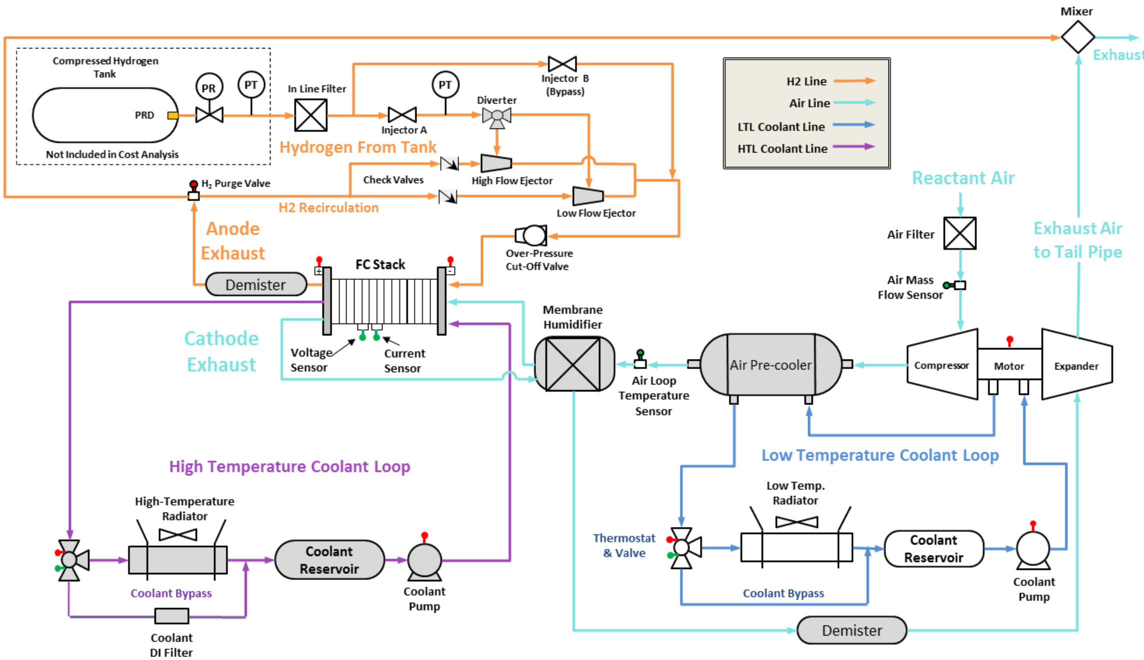




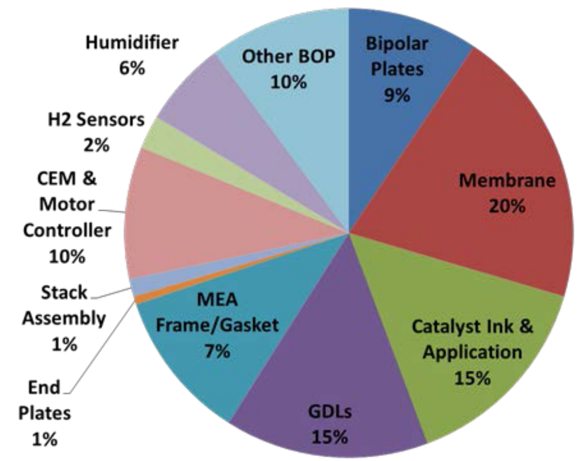


- Excluded components account for ~60% of system cost at 1k/year and ~30% at 100k/year
- Excluded items (primarily balance of system) cost reductions are due to favorable economies of scale
- The pressure vessel system cost is driven by carbon fiber cost which does not show economies of scale as favorable as balance of system

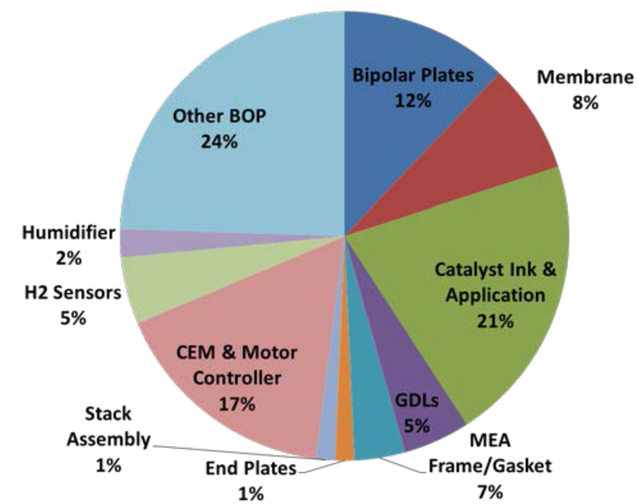
Fuel Cell System Cost Breakdown and System Diagram



Fuel Cell Stack Cost Breakdown (1,000 units/year)



Fuel Cell Stack Cost Breakdown (100,000 units/year)



- 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)

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