A Total Cost of Ownership Model for Design and Manufacturing Optimization of Fuel Cells in Stationary and Emerging Market Applications

Department of Energy Annual Merit Review for Fuel Cell Research
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Lawrence Berkeley National Laboratory

Project ID # FC098

This presentation does not contain any proprietary, confidential, or otherwise restricted information
Overview AMR 2015

Timeline

• Project start date: Oct 2011
• Project end date: Sept 2016
• Percent complete: 80%

Budget

• Total project funding
  – DOE share: 1.9M
  – Contractor share: n.a.
• FY15 DOE Funding: 270k
• Planned Funding for FY16: 100k

Barriers Addressed

• Fuel-cell cost: expansion of cost envelope to total cost of ownership including full life cycle costs and externalities (MYPP 3.4.5B)
• Lack of High-Volume Membrane Electrode Assembly Processes (MYPP 3.5.5A)
• Lack of High-Speed Bipolar Plate Manufacturing Processes (MYPP 3.5.5B)

Partners

• University of California Berkeley
  • Department of Mechanical Engineering Laboratory for Manufacturing and Sustainability
  • Transportation Sustainability Research Center
• Strategic Analysis
• Other Industry Advisors and Experts

DOE Cost Targets

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>2015 Target</th>
<th>2020 Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>10kW CHP System</td>
<td>$1900/kW</td>
<td>$1700/kW</td>
</tr>
<tr>
<td>100kW CHP System</td>
<td>$2300/kW</td>
<td>$1000/kW</td>
</tr>
</tbody>
</table>
Total-cost-of-ownership (TCO) modeling tool for design and manufacturing of fuel cells in stationary and materials-handling systems in emerging markets

Expanded framework to include life-cycle analysis (LCA) and possible ancillary financial benefits, including:
• carbon credits, health/environmental externalities, end-of-life recycling, reduced costs for building operation

Identify system designs that meet lowest manufacturing cost and TCO goals as a function of application requirements, power capacity, and production volume

Provide capability for sensitivity analysis to key cost assumptions

BARRIERS
• High capital and installation costs with a failure to address reductions in externalized costs and renewable energy value
• Potential policy and incentive programs may not value fuel cell (FC) total benefits.
Overview: Chemistries and Applications

• Fuel cell types to be considered:
  — Conventional, low-temp (~80° C) PEM fuel cell (LTPEM)
  — High-temp (~180° C) PEM fuel cell (HTPEM)
  — Solid oxide fuel cell (SOFC)

• Application Space:

<table>
<thead>
<tr>
<th>APPLICATION</th>
<th>SIZE [KW]</th>
<th>100</th>
<th>1000</th>
<th>10,000</th>
<th>50,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>STATIONARY POWER (P); COMBINED HEAT AND POWER (C)</td>
<td>1</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>C</td>
</tr>
<tr>
<td>Qtr</td>
<td>Due Date</td>
<td>Type</td>
<td>Milestones, Deliverables, or Go/No-Go Decision</td>
<td>Decision Criteria</td>
<td></td>
</tr>
<tr>
<td>-----</td>
<td>----------</td>
<td>------------</td>
<td>---------------------------------------------------------------------------------------------------------------</td>
<td>-------------------------------------------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>Q3</td>
<td>6/30/2014 Regular</td>
<td>Literature/patent summary and functional specifications completed for SOFC systems in co-generation and stationary power.</td>
<td>Status: Done</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Q4</td>
<td>9/30/2014 Go/No-Go</td>
<td>Go/No-Go project review meeting</td>
<td>Go Decision base on Go/No-Go Review Meeting 10/22/14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Q1</td>
<td>12/31/2014 Regular</td>
<td>Balance of plant, bill of materials, and manufacturing process flows defined for SOFC systems stationary power and CHP systems</td>
<td>Done</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Q2</td>
<td>3/31/2015 Regular</td>
<td>Manufacturing cost model completed for SOFC power and CHP systems</td>
<td>Done</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Q3</td>
<td>6/30/2015 Regular</td>
<td>Policy and energy system scenario analysis completed for LT PEM total cost models for CHP and backup power systems</td>
<td>In Progress</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Q4</td>
<td>9/30/2015 Go/No-Go</td>
<td>Total cost of ownership model and report completed for SOFC systems</td>
<td>Total cost of ownership model satisfactorily completed for SOFC systems in CHP and stationary power applications along with a report describing this work.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Approach: Milestone AOP Tracking 2015**
Approach: TCO Model Structure and Key Outputs

**Assumptions:**
- Application/ Size
- Mfg Volume/Yr
- Location (mfg, op)
- Prices
- Policies
- Fuel input
- Outages/Lifetimes

**Total Cost of Ownership (TCO) Model**

**Manufacturing Cost Model**
- Direct mfg costs
- Indirect mfg costs

**Lifecycle Cost Model**
- Capital/installation
- Fuel and operations
- Maintenance
- Stack replacements
- End of life

**Life Cycle Impact Assessment Models**
- Monetized health and GHG impacts

**Key Outputs:**
1) System manufacturing costs and “factory gate” prices
2) TCO Metrics: Levelized costs (/kWh), Total costs/yr
3) TCO including broader social costs
1 - Costing Approach

• Direct Manufacturing Costs
  - Capital costs
  - Labor costs
  - Materials costs
  - Consumables
  - Scrap/yield losses
  - Factory costs

• Global Assumptions
  - Discount rate, inflation rate
  - Tool lifetimes
  - Costs of energy, etc.

• Other Costs:
  - R&D costs, G&A, sales, marketing
  - Product warranty costs

Source: Altergy Systems
Combined Heat & Power Fuel Cell System (100kW example)

- Electricity Load Profile
- Cooling Load Profile
- Space Heating Load Profile
- Hot Water Load Profile

Fuel Cell

- Fuel Input
- GHG Emissions

Purchased Electricity

- Yes
- No

Purchased NG

Direct Use

Heat

Direct Use

Stored Thermal Energy

Cost

Avoided Emissions

Graphs:
- Daily electricity load profiles for small hotel in AZ
- Daily hot water load profiles for small hotel in AZ
3 - Life-Cycle Impact Assessment for Environmental and Health Externalities – Fuel Cell CHP Systems

Define Geography of Interest, Building Types

Building Load Shapes

Fuel Cell Load Shapes for Electricity and Heating

Displaced Heating Fuels  Displaced Grid Power

Net Change in Pollutant Emission Profile

Health Impact Model (APEEP Model)  Other Environmental Impacts (e.g., CO₂)

Monetized Impacts
TECHNICAL PROGRESS: SOFC FC SYSTEM MANUFACTURING COST
## CHP System Designs and Functional Specs

DFMA Manufacturing approaches for SOFC CHP and Power systems, anode-supported cell

<table>
<thead>
<tr>
<th>Component</th>
<th>Primary Approach</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anode*</td>
<td>Ni / YSZ Tape casting</td>
<td>Patent review, Industry input</td>
</tr>
<tr>
<td>Interlayer*</td>
<td>Ni 50% / YSZ 50% Screen printing</td>
<td>Patent review, Industry input</td>
</tr>
<tr>
<td>Electrolyte*</td>
<td>YSZ – Screen printing</td>
<td>Literature, patents, industry input</td>
</tr>
<tr>
<td>Interlayer*</td>
<td>LSM 50% / YSZ 50% - Screen printing</td>
<td>Literature, patents, industry input</td>
</tr>
<tr>
<td>Cathode*</td>
<td>Conducting Ceramic – Screen printing</td>
<td>Literature, industry input</td>
</tr>
<tr>
<td>Plates*</td>
<td>Stamped metal plates with SS441</td>
<td>Literature, patents, industry input</td>
</tr>
<tr>
<td>Seal/Frame MEA*</td>
<td>Framed EEA</td>
<td>Patents, industry input</td>
</tr>
<tr>
<td>Stack Assembly*</td>
<td>Partial to fully automated</td>
<td>Patents, Industry input</td>
</tr>
<tr>
<td>Endplate/ Seals*</td>
<td>Metal endplate</td>
<td>Industry input, literature</td>
</tr>
<tr>
<td>Test/Burn-in</td>
<td>Post Assembly 3 hrs</td>
<td>Industry input</td>
</tr>
</tbody>
</table>

*Full DFMA Costing analysis was performed
## Functional specs – common properties

<table>
<thead>
<tr>
<th>Common properties:</th>
<th>Near-Term</th>
<th>Future</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>System life</td>
<td>15</td>
<td>20</td>
<td>years</td>
</tr>
<tr>
<td>Stack life</td>
<td>24000</td>
<td>40000</td>
<td>hours</td>
</tr>
<tr>
<td>Reformer life (if app.)</td>
<td>5</td>
<td>10</td>
<td>years</td>
</tr>
<tr>
<td>Compressor/blower life</td>
<td>7.5</td>
<td>10</td>
<td>years</td>
</tr>
<tr>
<td>WTM sub-system life</td>
<td>7.5</td>
<td>10</td>
<td>years</td>
</tr>
<tr>
<td>Battery/startup system life</td>
<td>7.5</td>
<td>10</td>
<td>years</td>
</tr>
<tr>
<td>Turndown % (&gt;50 kW)</td>
<td>0</td>
<td>25</td>
<td>percent</td>
</tr>
<tr>
<td>Turndown % (&lt;50 kW)</td>
<td>25</td>
<td>50</td>
<td>percent</td>
</tr>
<tr>
<td>Expected Availability</td>
<td>96</td>
<td>98</td>
<td>percent</td>
</tr>
<tr>
<td>Stack cooling strategy</td>
<td>Air+off gas</td>
<td>Air+off gas</td>
<td>cooling</td>
</tr>
</tbody>
</table>

Turndown an area for further discussion but taking 25% for < 50kW systems currently.
### Functional Specs

#### 50kW CHP with Reformate Fuel

**System**
- **Gross system power**: 54.9 kW DC
- **Net system power**: 50 kW AC
- **Physical size**: 2x3x3 meter x meter x meter
- **Physical weight**: 3600 kg
- **Electrical output**: 480V AC Volts AC or DC
- **DC/AC inverter effic.**: 95.5% %
- **Waste heat grade**: 220 Temp. °C
- **Fuel utilization % (first pass)**: 85% %
- **Fuel input power (LHV)**: 84.23 kW
- **Stack voltage effic.**: 64% % LHV
- **Gross system electr. effic.**: 65.1% % LHV
- **Avg. system net electr. effic.**: 59.4% % LHV
- **Thermal efficiency**: 24.4% % LHV
- **Total efficiency**: 83.8% Elect.+thermal (%) FCE = 83.4% LHV; CFCL 82%

**Stack**
- **Stack power**: 54.86 kW
- **Total plate area**: 540 cm^2
- **Actively catalyzed area**: 329 cm^2 Est. 61% of tot. plate area
- **Single cell active area**: 299 cm^2 10% less than CCM area
- **Gross cell inactive area**: 45 %
- **Cell amps**: 105 A
- **Current density**: 0.35 A/cm^2 James 2012: 0.364mA/cm2
- **Reference voltage**: 0.8 V From James 2012 DOE
- **Power density**: 0.282 W/cm^2 James 2012: 0.291 W/cm2
- **Single cell power**: 84 W Nextech: 103 W/cell
- **Cells per stack**: 130 cells
- **Percent active cells**: 100 %
- **Stacks per system**: 5 stacks
50 kW SOFC CHP System with Reformate Fuel

- NG Supply
  - Subsystem B: Pre-treat
    - Burner
      - Subsystem C: Reactant Air Supply
        - Subsystem E: NG Supply
          - Subsystem F: Air Filter
          - Air Supply
          - 1 kW
          - Compressor
          - 50°C
          - Exhaust Air
          - Reactor Exhaust
            - 25°C
          - Burner Exhaust
            - 660°C
            - 600°C
            - 200°C
          - React. Air Heat
            - 600°C
            - 50 kW (net AC)
            - 180°C
            - 200°C
            - 180°C
          - 700°C
          - NG/reformate
            - 75% NG
          - 600°C
          - 200°C
          - 700°C
          - 50 kW SOFC CHP System with Reformate Fuel
          - Controls/Meters
            - 650°C
            - 25°C
          - Liquid Pumps
            - 75% NG
          - Fuel Air H2O Coolant Power
          - Subsystem G: Controls/Meters
          - Thermal Host
            - 50°C
            - 180°C

T. Lipman - DOE FC TCO Project
Manufacturing Cost Model – EEA, Metal Plates

EEA Process Flow - Cathode Coating Line

Metal Plate Process Flow

EEA Cost Plot - 50kW System

Plates Cost Plot - 50kW System
Seal/Frame Cost Analysis

• Seal/frame cost ($/kW)

![Graphs showing Seal/Frame Cost ($/kW) for 10 kWe and 50 kWe systems.](image)

Cell to frame seal BOM (US Patent 8,691,470 B2)

<table>
<thead>
<tr>
<th>Material</th>
<th>Wt %</th>
<th>Cost ($/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CaO</td>
<td>15.5</td>
<td>84</td>
</tr>
<tr>
<td>BaO</td>
<td>9</td>
<td>117</td>
</tr>
<tr>
<td>Al2O3</td>
<td>14.5</td>
<td>71</td>
</tr>
<tr>
<td>SiO2</td>
<td>56</td>
<td>112</td>
</tr>
<tr>
<td>K20</td>
<td>5</td>
<td>1.6</td>
</tr>
</tbody>
</table>
System Cost for 10/50kW CHP SOFC

- Stack cost dominated by EEA then seal/frame at high volumes
- BOP_Non-FP and BOP_Fuel processor are 50%-80% of overall cost
- System direct cost < $800/kW at high volumes
BOP Components Cost Breakdown

- Balance of plant: about 40% power subsystem, 20% controls/metering, 15% fuel processing
## Equipment Cost Estimates vs. DOE Targets

<table>
<thead>
<tr>
<th>System</th>
<th>Units/yr</th>
<th>2020 DOE Target w/ Markup ($/kW)</th>
<th>LT PEM direct cost ($/kW)</th>
<th>LT PEM cost with 50% markup ($/kW)</th>
<th>SOFC direct cost ($/kW)</th>
<th>SOFC cost with 50% markup ($/kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DOE Targets</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10kW CHP System</td>
<td>50,000</td>
<td>$1,700</td>
<td>$1,724</td>
<td>$2,586</td>
<td>$1,170</td>
<td>$1,105</td>
</tr>
<tr>
<td>100kW CHP System</td>
<td>1000</td>
<td>$1000</td>
<td>$1,200</td>
<td>$1,800</td>
<td>$940</td>
<td>$1,410</td>
</tr>
<tr>
<td><strong>This Work</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>10 kW SOFC system close to 2020 DOE target</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
TECHNICAL PROGRESS: HT PEM SYSTEM AND TCO COST MODELING
HT PEM vs LT PEM

- Higher stack cost for HT PEM because of lower power density and larger plate size, higher Pt loading, and different design
- Somewhat lower BOP/FP cost for HT PEM (simpler system), and a lower fraction of system costs
- Overall HT PEM: 10-15% higher system costs at low volume than LT PEM, up to 30% higher cost at 100kW, high volume
- LT PEM: Non-stack costs dominate
HT PEM Total cost of ownership

TCO model includes New York, Chicago, Minneapolis, Phoenix, Houston, and San Diego settings with various commercial buildings

**FC CHP is most favorable in regions with higher carbon intensity electricity** (Chicago and Minneapolis)

50kW Small Hotel in Minneapolis
HT PEM system with WH+ SH
Installed cost $3,400/kWe

10kW Small Hotel in Chicago
HT PEM system with WH+SH
Installed cost $4,400/kWe
TECHNICAL PROGRESS: COMPARISONS TO MARKET DATA AND OTHER MODELED COSTS
Japan Micro CHP (LT PEM) – LBNL cost modeling can help disaggregate cost reductions

- 12% Learning curve from 2009-2014, nominal 0.7-1kW
- 42% cost reduction observed from 2009 to 2013

**LEARNING CURVE, PRICES (2009-2014)**

- LBNL Cost model implies about 23% cost reduction from economies of scale (estimate ~1300 units/yr, 2009 to about 15,000 units/yr, 2013 per vendor)
- About 19% cost reduction estimated based on publically announced design and performance improvements; about 7% cost reduction attributed to other factors.
- These three factors give the observed 42% cost reduction from 2009-2013.

**LEARNING CURVE**

\[ y = 148334x^{0.176} \]

\[ R^2 = 0.9485 \]

**Prices (2009-2014)**

<table>
<thead>
<tr>
<th>Year</th>
<th>Price (2013$)</th>
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</thead>
<tbody>
<tr>
<td>2009</td>
<td>$20,000</td>
</tr>
<tr>
<td>2014</td>
<td>$10,000</td>
</tr>
</tbody>
</table>

**LBNL DIRECT COST MODEL**

- System Cost [2013$]
- Annual Production Volume (Systems/year)
- Capital Cost
- Building Cost
- Labor
- Materials
- Variable Cost
- Balance of Plant (Non-Fuel Processor)
- Balance of Plant (Fuel Processor)
- Scrap
- Corporate markup and other soft costs (75%)

2013 Price: $20,000
LT PEM: LBNL 2014 vs SA 2012 cost comparison

<table>
<thead>
<tr>
<th>Trial No.</th>
<th>100 sys/yr</th>
<th>1,000 sys/yr</th>
<th>10,000 sys/yr</th>
<th>50,000 sys/yr</th>
<th>Changed Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>SA Study (2012)</td>
<td>351</td>
<td>272</td>
<td>161</td>
<td>123</td>
<td>Pt loading= 0.4mg/cm²; Pt cost=$36/g (based on $1,100/tr.oz); Power density= 0.408W/cm²; Yield assumptions &gt;99.5% for all stack modules.</td>
</tr>
<tr>
<td>0 (Actual Assumptions of LBNL Study)</td>
<td>556</td>
<td>346</td>
<td>273</td>
<td>238</td>
<td>Discount Rate=15%; Pt price $57.6/g; and Pt loading= 0.5mg/cm²; power density=0.354W/cm²; Yield (see Table on right)</td>
</tr>
<tr>
<td>1</td>
<td>467</td>
<td>276</td>
<td>210</td>
<td>178</td>
<td>Pt loading=0.4mg/cm² &amp; pt price $36/g and yield=99.5% for all FC stack modules</td>
</tr>
<tr>
<td>2</td>
<td>509</td>
<td>299</td>
<td>226</td>
<td>192</td>
<td>Pt price $36/g only</td>
</tr>
<tr>
<td>3</td>
<td>472</td>
<td>291</td>
<td>221</td>
<td>187</td>
<td>Discount Rate=10% and Pt price $36/g</td>
</tr>
<tr>
<td>4</td>
<td>494</td>
<td>284</td>
<td>211.4</td>
<td>177</td>
<td>Pt loading= 0.5 mg/cm²</td>
</tr>
<tr>
<td>5</td>
<td>457</td>
<td>276</td>
<td>207</td>
<td>173</td>
<td>Discount Rate=10%; Pt price $36/g; and Pt loading= 0.4mg/cm²</td>
</tr>
<tr>
<td>6</td>
<td>386</td>
<td>239</td>
<td>181</td>
<td>152</td>
<td>Discount Rate=10%; Pt price $36/g; and Pt loading= 0.4mg/m²; power density=0.408W/cm²; Yield=99.5% for all stack modules</td>
</tr>
</tbody>
</table>

Trial 6 Delta from SA, matched conditions | 10% | -12% | 12% | 24% |
Trial 2 vs Trial 0 (Pt impact only of LBNL cost) | 15% | 16% | 19% | 21% |

- Different assumptions: Pt price, Disc. Rate, yield, power density
  - SA's 2014 AMR update increased Pt cost to $1500/tr. oz (or $49/g) from $1100/tr. oz above. This is much closer to LBNL's assumed Pt price of $57.60/g
- LBNL / SA within 20% of each other with matched assumptions
  - LBNL estimates are higher cost; possibly more detailed in process flows
Responses to 2014 AMR Reviewer Comments

1. “De-prioritize” HT PEM – An initial HT PEM cost analysis report was completed in Q4’14, but the focus of the team’s efforts have been on SOFC systems.

2. Increase industry inputs/collaborators – The team has increased the number of industry inputs and reviewers, including VersaPower(FCE), SOFCpower, Minh Nguyen of University of California, San Diego (formerly of GE fuel cells), Jack Brouwer of University of California, Irvine, and Massimo Santarelli of Polytechnic University of Turin. Strategic Analysis is also a collaborator on the project.

3. Compare with known cost numbers and cost modeling – This update contains several slides describing LBNL cost estimates vs. SA and known price data on Japanese micro-CHP and stationary fuel cell systems in California.

4. Clarify value of work vis a vis SA's previous DFMA, etc. - This work is part of a complimentary portfolio of DOE analysis projects. Other projects have focused on different applications (e.g., MHE, passenger vehicles). This project also expands the direct cost modeling approach to include life-cycle costing and ancillary financial benefits (GHG credits, health and environmental impacts).

5. BOP opportunities - This work continues to highlight the importance of balance of plant cost reduction for overall system cost reduction (e.g., power conditioning, potential cost reduction from design and integration). We have identified power conditioning as a key area for CHP systems. There are many parts in the balance of plant contributing to the overall cost, and increased parts-integration is a potential cost reduction opportunity.

6. Include Incentives – Both federal and state incentive programs and scenarios will be included in the SOFC life-cycle cost modeling Q3’15.
Collaborations

Partners

University of California, Berkeley
Laboratory for Manufacturing and Sustainability, Dept. of Mechanical Engineering:

— Manufacturing process analysis, DFMA analysis

University of California, Berkeley
Transportation Sustainability Research Center and DOE Pacific Region Clean Energy Application Center:

— System and BOP design, functional specs, BOM definition, parametric relationships
— CHP applications and functional requirements

Strategic Analysis

— SOFC system design and functional specifications

Other Collaborators

— No other funded subcontracts, but many industry contacts and expert reviewers, shown on next slide.
Industry/expert inputs and reviews conducted below and will continue

Functional specs and system design:
• Strategic Analysis (sub-con)
• Brian Borglum, Versa Power/FCE

General system and manufacturing:
• SOFCpower, Mezzolombardo, Italy visit, 18 October 2014
• Minh Nguyen, University of California, San Diego (formerly of GE)
• Prof. Massimo Santarelli of Polytechnic University of Turin, Italy

Balance of plant:
• Jack Brouwer, University of California, Irvine
Remaining Challenges

• System and stack data availability for electrolyte-supported SOFC stack
• Low volume costing and yield modeling
• Modeling the transition from manual to automated automation
• Lack of data for system availability – will add as a sensitivity factor to LCC model
Proposed Future Work

- LCC and TCO model for SOFC systems including absorption cooling option (Q3-Q4’15)
- Scenario modeling of stationary FC systems: incentives, future gas and electricity prices, future H₂ supply (Q3-Q4’15)
- Updating LT PEM TCO model, material prices, balance of plant costs (Q1-Q2’16)
- Automating SOFC TCO model for user enabled interface in Analytica (Q1-Q2’16)
- Case study analysis of key cost reduction opportunities in BOP, e.g., power conditioning and inverters (Q2’16)
- Updated SOFC TCO model, material prices, BOP costs, and scenario/sensitivity analysis (Q2-Q3’16)
- Final updated reports for LT PEM and SOFC TCO modeling (Q3-Q4’16)
Project Summary

Relevance: Provide more comprehensive cost analysis for stationary and materials handling fuel cell systems in emerging markets including ancillary financial benefits.

Approach: Design for manufacturing and assembly (DFMA) analysis cost model and integrated lifecycle cost analysis (LCA) impacts including life cycle costs, carbon credits, and health and environmental benefits.

Technical Accomplishments and Progress: Direct cost model for SOFC CHP and electric power systems; Total cost of ownership model for HT PEM CHP systems (manufacturing cost model, LCC model and externality valuation);

Collaboration: Partnerships with UC-Berkeley manufacturing analysis and transportation sustainability research groups and collaboration with Strategic Analysis

Proposed Next-Year Research: Total cost of ownership model for SOFC CHP/Power systems and updating of PEM manufacturing cost and TCO models

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Acknowledgment

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Thank you
mwei@lbl.gov
## Global DFMA Costing assumptions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Units</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating hours</td>
<td>$t_{hs}$</td>
<td>varies</td>
<td>Hours</td>
<td>8 hours base shift; [1,1.5,2] shifts</td>
</tr>
<tr>
<td>Annual Operating Days</td>
<td>$t_{dy}$</td>
<td>250</td>
<td>Days</td>
<td>52wks*5days/wk-10 vacation days</td>
</tr>
<tr>
<td>Production Availability</td>
<td>$A_m$</td>
<td>0.85</td>
<td></td>
<td>Typical value in practice</td>
</tr>
<tr>
<td>Avg. Inflation Rate</td>
<td>$j$</td>
<td>0.026</td>
<td></td>
<td>US avg. for past 10 years‡</td>
</tr>
<tr>
<td>Avg. Mortgage Rate</td>
<td>$j_m$</td>
<td>0.05</td>
<td></td>
<td>See following reference †††‡‡‡‡</td>
</tr>
<tr>
<td>Discount Rate</td>
<td>$j_d$</td>
<td>0.10</td>
<td></td>
<td>Typical value</td>
</tr>
<tr>
<td>Energy Inflation Rate</td>
<td>$j_e$</td>
<td>0.056</td>
<td></td>
<td>US avg of last 3 years‡‡‡‡</td>
</tr>
<tr>
<td>Income Tax</td>
<td>$i_i$</td>
<td>0</td>
<td></td>
<td>No net income</td>
</tr>
<tr>
<td>Property Tax</td>
<td>$i_p$</td>
<td>0.014</td>
<td></td>
<td>US avg from 2007†</td>
</tr>
<tr>
<td>EOL Salvage Value</td>
<td>$k_{eol}$</td>
<td>0.02</td>
<td></td>
<td>Assume 2% of end-of-life value</td>
</tr>
<tr>
<td>Tool Lifetime</td>
<td>$T_t$</td>
<td>15</td>
<td>Years</td>
<td>Typical value in practice</td>
</tr>
<tr>
<td>Energy Tax Credits</td>
<td>$ITC$</td>
<td>0</td>
<td>Dollars</td>
<td></td>
</tr>
<tr>
<td>Energy Cost</td>
<td>$c_e$</td>
<td>0.1</td>
<td>$/kWhe</td>
<td>Typical U.S. value</td>
</tr>
<tr>
<td>Floor space Cost</td>
<td>$c_{fs}$</td>
<td>1291</td>
<td>$/m^2$</td>
<td>US average for factory††</td>
</tr>
<tr>
<td>Building Depreciation</td>
<td>$j_{hr}$</td>
<td>0.031</td>
<td></td>
<td>BEA rates†††</td>
</tr>
<tr>
<td>Building Recovery</td>
<td>$T_{hr}$</td>
<td>31</td>
<td>Years</td>
<td>BEA rates†††</td>
</tr>
<tr>
<td>Building Footprint</td>
<td>$a_{br}$</td>
<td>Varies</td>
<td>m²</td>
<td></td>
</tr>
<tr>
<td>Line Speed</td>
<td>$v_l$</td>
<td>Varies</td>
<td>m/min</td>
<td>Approximation from DTI2010 (James et al., 2010)</td>
</tr>
<tr>
<td>Web Width</td>
<td>$W$</td>
<td>Varies</td>
<td>M</td>
<td>Lower widths at low volume</td>
</tr>
<tr>
<td>Hourly Labor Cost</td>
<td>$c_{labor}$</td>
<td>28.08</td>
<td>$/hr$</td>
<td>Hourly wage per worker</td>
</tr>
</tbody>
</table>
## Materials Prices

<table>
<thead>
<tr>
<th>Vendor/Country</th>
<th>Material</th>
<th>Price</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Anode backing layer</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AIICHI JITSUGYO (Japan)</td>
<td>Nickel Oxide</td>
<td>$65-70/kg for 1,000kg order $40-45/kg for 5,000kg order $35-40/kg for 10,000kg order $32-37/kg for 20,000kg order</td>
<td>Anode backing layer</td>
</tr>
<tr>
<td><strong>Electrolyte layer</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AIICHI JITSUGYO (Japan)</td>
<td>8YSZ (8mol%YSZ)</td>
<td>$75-80/kg for 100kg order $65-70/kg for 1,000kg order $60-65/kg for 5,000kg order</td>
<td>Electrolyte layer</td>
</tr>
<tr>
<td>Daiichi (Japan)</td>
<td>8YSZ (8mol%YSZ)</td>
<td>100kg by sea shipment: $95/kg 1,000kg by sea shipment: $83/kg 100kg by air shipment: $97/kg</td>
<td>Electrolyte layer</td>
</tr>
<tr>
<td>Daiichi (Japan)</td>
<td>Scandia Stabilized Zirconia(10ScSZ):</td>
<td>100kg by sea shipment: $524/kg 1,000kg by sea shipment: $515/kg 100kg by air shipment: $526/kg</td>
<td>Electrolyte layer (Electolyte-supported cell)</td>
</tr>
<tr>
<td>Inframat Advanced Materials (USA)</td>
<td>8mol%YSZ powder</td>
<td>$150 per kg; if order&gt;100kg</td>
<td>Electrolyte layer</td>
</tr>
<tr>
<td>Inframat Advanced Materials (USA)</td>
<td>LSM powder</td>
<td>$150 per kg; if order&gt;100kg</td>
<td>Cathode layer</td>
</tr>
<tr>
<td>Qingdao Terio Corporation (China)</td>
<td>LSM powder</td>
<td>$250 per kg</td>
<td>Cathode layer</td>
</tr>
<tr>
<td>Hebei Baicheng (China)</td>
<td>Cerium Oxide (Doped Ceria)</td>
<td>$13.5 per kg</td>
<td>Inter-layers (Electolyte-supported cell)</td>
</tr>
<tr>
<td>Changsha Asian Light Economic Trade Co. (China)</td>
<td>Cerium Oxide (Doped Ceria); purity:99.95%</td>
<td>$2,667 per ton</td>
<td>Inter-layers (Electolyte-supported cell)</td>
</tr>
<tr>
<td><strong>Cathode layer</strong></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td><strong>Glass Seal</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spectrum Chemical M</td>
<td>CaO</td>
<td>$84/kg</td>
<td>Alkaline-earth based silicate glass</td>
</tr>
<tr>
<td>Fisher Scientific (USA)</td>
<td>BaO</td>
<td>$117/kg</td>
<td>Alkaline-earth based silicate glass</td>
</tr>
<tr>
<td>Fisher Scientific (USA)</td>
<td>Al2O3</td>
<td>$71/kg</td>
<td>Alkaline-earth based silicate glass</td>
</tr>
<tr>
<td>Alibaba (China)/Shijiaz</td>
<td>SiO2</td>
<td>$112/kg</td>
<td>Silicate glass</td>
</tr>
<tr>
<td></td>
<td>K2O</td>
<td>$1550/metric ton</td>
<td>Alkaline-earth based silicate glass</td>
</tr>
<tr>
<td><strong>Metal Seal</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Infomine.com</td>
<td>Ag</td>
<td>$19.73/troy ounce</td>
<td>Brazing alloy</td>
</tr>
<tr>
<td>Infomine.com</td>
<td>Cu</td>
<td>$3.06/lb</td>
<td></td>
</tr>
<tr>
<td>Infomine.com</td>
<td>TiH2</td>
<td>$0.025/g</td>
<td>Promotes wetting brazing of Ag-based alloys and enhances the sealing properties</td>
</tr>
</tbody>
</table>
Yield Assumptions

<table>
<thead>
<tr>
<th>FC Size (kW)</th>
<th>10</th>
<th>10</th>
<th>10</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual Production Volume</td>
<td>100</td>
<td>1,000</td>
<td>10,000</td>
<td>50,000</td>
</tr>
<tr>
<td>EEA Yield</td>
<td>95.00%</td>
<td>96.00%</td>
<td>97.00%</td>
<td>98.00%</td>
</tr>
<tr>
<td>Interconnect &amp; Frame</td>
<td>85.00%</td>
<td>85.65%</td>
<td>92.67%</td>
<td>97.91%</td>
</tr>
<tr>
<td>Seal</td>
<td>85.00%</td>
<td>85.77%</td>
<td>92.79%</td>
<td>98.04%</td>
</tr>
<tr>
<td>Assembly</td>
<td>99.5%</td>
<td>99.5%</td>
<td>99.5%</td>
<td>99.5%</td>
</tr>
<tr>
<td>Stack Average Yield</td>
<td>89.8%</td>
<td>90.3%</td>
<td>95.0%</td>
<td>98.5%</td>
</tr>
</tbody>
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</tr>
</tbody>
</table>

- Versa power reported yield numbers >95% for EEA

SOFC Stack cost in ($/kW)
External Damages from all Pollutants by County

- Focus on ambient concentrations of PM$_{2.5}$ and O$_3$ (dominant health and environmental externalities)