POWER GENERATION FROM AN INTEGRATED BIOMASS REFORMER AND SOLID OXIDE FUEL CELL

SBIR Phase III  Xlerator Program

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INNOVATEK

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

Timeline
Start: 10-01-2010
Finish: 03-31-2014
66% Complete

DOE Barriers: Cost, Durability & Performance

DOE Targets: H2 production from diverse domestic sources; distributed power demo 2Q 2018

<table>
<thead>
<tr>
<th>Year</th>
<th>Cost/kW</th>
<th>Efficiency</th>
<th>Lifetime</th>
<th>Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015</td>
<td>$1700</td>
<td>42.5%</td>
<td>40,000h</td>
<td>5 kW Dist Gen Sys</td>
</tr>
<tr>
<td>2020</td>
<td>$1500</td>
<td>&gt;45%</td>
<td>60,000h</td>
<td>5 kW Dist Gen Sys</td>
</tr>
</tbody>
</table>

Budget
Total: $2.3M
Received FY12: $650K
Expected FY 13: $748K

Partners
Topsoe Fuel Cell
Fuel Cell Energy/Versa Power
Impact Washington
Relevance: Public Benefits; H₂ from Diverse Sources

Addressing DOE Barriers and Targets: Environmental Quality & Energy Security

The full benefits from fuel cells are possible only if the feedstock for hydrogen production is a renewable, domestically produced commodity that does not compete in the food chain, and does not increase the price of energy.

Our technology will address these issues by:

- Helping shift the primary energy source for H₂ from fossil fuels to renewable non-food biomass, using natural gas as the bridge.
- Using less fuel through high system efficiency by effective thermal integration and off-gas recycling.
- Providing an alternative method for distributed power generation near the source of the feedstock, enhancing grid stability at competitive cost.
# Relevance: Project Objectives

<table>
<thead>
<tr>
<th>Year</th>
<th>Objective</th>
<th>DOE Barriers Addressed</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011</td>
<td>Establish design to meet technical and operational needs for distributed energy production from renewable fuels</td>
<td>SOFC power using renewable non-food biomass fuel; codes &amp; standards</td>
</tr>
<tr>
<td>Complete</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2011/2012</td>
<td>Design, optimize, and integrate proprietary system components and balance-of-plant in a highly efficient design.</td>
<td>Demonstration; system efficiency; design for low cost manufacturing</td>
</tr>
<tr>
<td>Complete</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
| 2013/2014  | Demonstrate the technical and commercial potential of the technology for energy production, emissions reduction, and process economics                                                                 | • 40,000 h lifetime  
• 99% availability  
• >40% efficiency  
• $1700/kW equipment cost |
Approach: Project Goal

Develop and demonstrate a fuel cell distributed energy system that operates with 2\textsuperscript{nd} generation biofuel.

- System based on InnovaTek’s steam reforming process and SOFC
- Non-food biofuels include pyrolysis oil and bio-kerosene processed locally
- System to be demonstrated in Richland’s renewable energy park and tied to grid

Mid-Columbia Energy Initiative:
Meets 2020 electrical load growth needs with renewables.
### Approach: Milestones & Go/No Go

<table>
<thead>
<tr>
<th>Date</th>
<th>Milestone or Go/No Go</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan 2013</td>
<td>M4: Achieve 40% system operating efficiency with revised/optimized system design</td>
<td>41%</td>
</tr>
<tr>
<td>Feb 2013</td>
<td>M5: System performance proves superior energy efficiency &amp; emissions reductions compared to conventional technology</td>
<td>Complete</td>
</tr>
<tr>
<td>March 2013</td>
<td>Go/No Go: Analysis of process economics supports commercial feasibility (Cost of power is competitive)</td>
<td>Complete</td>
</tr>
<tr>
<td>Oct 2013</td>
<td>Complete fabrication of Gen3 prototype for field demonstration</td>
<td>Not started</td>
</tr>
<tr>
<td>March 2014</td>
<td>Complete 6 months of field demonstration</td>
<td>Not started</td>
</tr>
</tbody>
</table>
Approach: Optimization & Economic Analysis

1. Use simulation and modeling studies to optimize system design for performance and cost reduction.
   - Optimize process configuration using MathCAD and FEMLAB
   - Conduct FMEA to assess necessary redesign, determine maintenance requirements and costs, lifetime
   - Conduct DFMA analyses to identify design changes to improve manufacturability and reduce production & operation costs
   - Use HOMER model to assess cost of power

2. Translate dimensions, geometries, and flow patterns defined from optimization modeling to 3-D CAD images

3. Complete Bill of Materials & SolidWorks drawing libraries for all original hardware designs and BOP
   - Use this information to model capital equipment costs and parasitic power requirements
Approach: Scale-up & Optimize Core Technology

InnovaGen® Fuel Processor for 4 kW power

- Creates hydrogen from a range of liquid and gaseous fuels with high energy density
- Proprietary catalyst & hardware
- Water neutral steam reformer
- Compact and efficient

Solid Oxide Fuel Cell

2012          2013
Size reduced, output increased

Transitioning to scaled-up SOFC
Approach: Economic Analysis Models

**Techno-Economics Model**
- Design and Costs
- SolidWorks® CAD Software
- Bill of Materials
- DFMA® Software
- System operation (efficiency, life, load); Fuel data & cost

**Financial Model (Excel)**
- Personnel
- Operating Expenses
- Property and Equipment; Financing
- Cost of Revenues
- Market Data, by Niche
- Sales/Licensing Projection
- Contract R&D

**HOMER Software**
- Analyzes cost of power
- Financial: Determines business viability

**Cost of Energy**
- Breakdown of costs by type
- Sensitivity analysis

**Balance Sheet**

**Income Statement**

**Cash Flows**

Legend:
- Blue = Data Input
- Purple = Software/Calculations
- Green = Output
- Data flow
Accomplishments: Developed Highly Efficient Thermally Integrated System Design

Process Flow Diagram
- Subdivided into 21 process streams

Mass and Energy Balance
- Completed for each process stream
- Determines input, output, efficiency

Optimized Layout, Piping & Instrumentation

Solid Model of Integrated System

Component Design and Analysis
- Process simulations
- Design trade-off analyses

5kW fuel cell system that operates on liquid bio-fuel
Accomplishments: Solid Model 4 kW

Design includes complete Bill of Materials and P&ID
Part count reduced by ~74%
Cost reduced by ~40%

Hot Box Subassembly

Fully Integrated System
### Accomplishments: 41% System Efficiency

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gross DC Power, kW</td>
<td>4.2</td>
</tr>
<tr>
<td>Current density, mA/cm²</td>
<td>390</td>
</tr>
<tr>
<td>Cell active area, cm²</td>
<td>550</td>
</tr>
<tr>
<td>Stack current, A</td>
<td>214.5</td>
</tr>
<tr>
<td>Cell voltage, volt</td>
<td>0.82</td>
</tr>
<tr>
<td>Number of cells</td>
<td>24</td>
</tr>
<tr>
<td>gross DC power, watt</td>
<td>4221</td>
</tr>
<tr>
<td>stack electrical efficiency</td>
<td>65.60%</td>
</tr>
<tr>
<td>parasitic power, watts</td>
<td>300</td>
</tr>
<tr>
<td>Net AC electrical efficiency</td>
<td>40.8%</td>
</tr>
</tbody>
</table>

Improved from last year (37.5%) due to:
- Better stack efficiency
- Lower parasitic power due to lower stack pressure drop
- Less waste heat loss through improved thermal integration and heat transfer
- Higher methane content in reformate
Accomplishments: Catalyst Durability

100% conversion of bio-kerosene for >900 hrs
Accomplishments: Analysis of Energy Cost

Adapted EERE’s HOMER Model for fuel cell system

- Examined several scenarios for delivering 5 kW electrical AC power for 10 years using InnovaGen FC power unit
- Compared bio-kerosene & natural gas
- Capitol and operating costs based on Bill of Materials and Testing
- Used projected production and fuel pricing data from DOE sources

Significant Findings:

1. Our fuel cell generator operating on natural gas could produce electricity at prices at or below current grid prices (<$0.09/kWh) when volume production brings capital costs down.

2. The price for liquid bio-fuel, estimated at $3.50 per gallon, is the dominant factor affecting cost of electricity when operating on bio-fuel.
Progress: Economic Analysis for 5 kW FC

Cost of energy using InnovaTek’s 5 kW fuel cell system with n.gas at current & forecasted spot price

- **Natural Gas 2013**: $0.147/m³
- **Natural Gas 2040**: $0.277/m³

<table>
<thead>
<tr>
<th></th>
<th>Natural Gas 2013</th>
<th>Natural Gas 2040</th>
<th>Bio-fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total net present cost</td>
<td>$37,938</td>
<td>$48,329</td>
<td>$104,959</td>
</tr>
<tr>
<td>Levelized cost of energy</td>
<td>$0.107/kWh</td>
<td>$0.136/kWh</td>
<td>$0.295/kWh</td>
</tr>
<tr>
<td>Operating cost</td>
<td>$3,222/yr</td>
<td>$4,503/yr</td>
<td>$11,485/yr</td>
</tr>
</tbody>
</table>

Cost of energy using InnovaTek’s 5 kW fuel cell system using bio-kerosene with Honeywell’s projected price

- **Bio-kerosene**: $3.50/gal
Progress: 32% Cost Reduction Fuel Processor

<table>
<thead>
<tr>
<th>Reformer System</th>
<th>Labor Cost</th>
<th>Material Cost</th>
<th>Total Cost</th>
<th>Parts</th>
<th>Approx Volume (L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original Design</td>
<td>$10,201</td>
<td>$4951</td>
<td>$15,152</td>
<td>159</td>
<td>13.87</td>
</tr>
<tr>
<td>Revised Design</td>
<td>$6,374</td>
<td>$3997</td>
<td>$10,371</td>
<td>66</td>
<td>6.88</td>
</tr>
</tbody>
</table>

Reformer Design Comparison

Old Design
- Material Cost
- Labor Cost

New Design
- Material Cost
- Labor Cost
Progress: 79% Cost Reduction Fluid Handling

<table>
<thead>
<tr>
<th>Subassembly</th>
<th>Design</th>
<th>Labor Cost</th>
<th>Material Cost</th>
<th>Total Cost</th>
<th>Parts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Delivery</td>
<td>Original</td>
<td>$210</td>
<td>$2,630</td>
<td>$2,840</td>
<td>136</td>
</tr>
<tr>
<td></td>
<td>Revised</td>
<td>$22.50</td>
<td>$762</td>
<td>$785</td>
<td>16</td>
</tr>
<tr>
<td>Fuel &amp; Fuel Delivery</td>
<td>Original</td>
<td>$390</td>
<td>$11,573</td>
<td>$11,963</td>
<td>118</td>
</tr>
<tr>
<td></td>
<td>Revised</td>
<td>$60</td>
<td>$2,230</td>
<td>$2,290</td>
<td>25</td>
</tr>
</tbody>
</table>
Collaborations

Subcontractors
- Fuel Cell Energy – Versa Power SOFC (within DOE H₂ Program)
- Boothroyd Dewhurst – Design for Manufacturing & Assembly training
- Manufacturing partners – shift from welding to brazing

Strategic Partners
- Impact Washington – manufacturing design support
- PNNL – provided upgraded bio-oil made from non-food biomass (within DOE H₂ Program)
- Honeywell UOP – provides bio-kerosene
- City of Richland Electric Utility – providing site for field demo
- Mid-Columbia Energy Initiative

Education
- Supported 3 student interns from WSU, U of WA, Delta HS in mechanical engineering and chemistry
Proposed Future Work

Objective 3. Prove the technical and commercial potential of the technology

**FY13**
- Optimize performance by testing & adjusting operating parameters
- Further improve system efficiency & durability; reduce cost
  - Enhance FC-FP integration; evaluate BOP alternatives

**FY14**
- Fabricate and assemble fully integrated grid-ready 5 kW system
- Verify performance and durability with 6 month field demo at City Utility
- Analyze process economics
Summary

Relevance: Shift primary energy from fossil to renewable fuels
• Address codes & standards for fuel cells
• Increase system efficiency, lifetime and durability; decrease cost
• Distributed power production near source of feedstock to enhance grid stability

Approach: Develop reformer that generates hydrogen from non-food biofuels
• Develop highly efficient processing design of integrated SOFC and fuel processor
• Prove technology in long-term field demonstration with utility partner

Accomplishments: Achieved 41% system efficiency
• Used simulation and modeling to optimize component & system designs
• Prepared solid model of system & complete Bill of Materials with P&ID
• Developed optimized catalyst for biofuel reforming; demonstrated >900hrs durability
• Determined capital and operating expenses; modeled process economics

Collaborations: Supported 3 students; Subcontractors for fuel cell & manufacturers;
• Partnerships with PNNL, WSU, Boeing, City of Richland, Regional Energy Initiative

Future: Complete laboratory tests with 4 kW prototype
• Fabricate prototypes for grid interconnect
• Conduct field demonstration and long term operation
• Complete further analysis of process economics
Technical Back-up
Technical: System Efficiency Algorithms

system efficiency (electrical efficiency)

\[ P_{\text{parasitic}} := 300 \text{W} \]

regulated DC power

\[ DC_{\text{reg}}(I_d) := DC_{\text{gross}}(I_d) \cdot \eta_{\text{dc\_dc}} \]

net DC power

\[ DC_{\text{net}}(I_d) := DC_{\text{reg}}(I_d) - P_{\text{parasitic}} \]

net AC power

\[ AC_{\text{net}}(I_d) := DC_{\text{net}}(I_d) \cdot \eta_{\text{dc\_ac}} \]

\[ \eta_{\text{ele}} := \frac{AC_{\text{net}}(I_d)}{LHV_{\text{spk}} \cdot (n_{\text{feed}} + n_2) \cdot MW_{\text{spk}}} = 40.793\% \]

\[ \eta_{\text{ele}} = 0.408 \]

\[ \eta_{\text{fps}} := \frac{LHV_{\text{H}_2} \cdot N_{\text{anode\_in}_3} + LHV_{\text{CH}_4} \cdot N_{\text{anode\_in}_0} + LHV_{\text{CO}} \cdot N_{\text{anode\_in}_1}}{LHV_{\text{spk}} \cdot (n_{\text{feed}} + n_2) \cdot MW_{\text{spk}}} = 112.977\% \]

\[ DC_{\text{gross}}(I_d) = 4.221 \times 10^3 \text{ W} \]

\[ \eta_{\text{dc\_dc}} := 95\% \]

\[ \eta_{\text{dc\_ac}} := 92\% \]

\[ OCV_{\text{H}_2} := 1.48 \text{volt} \]

\[ OCV_{\text{L}_2} := 1.25 \text{volt} \]

\[ \eta_{\text{volt}} := \frac{\text{Vol}t800_{\text{cell}}}{OCV_{\text{L}_2}} = 0.656 \]