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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Project ID: FC096

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Overview

Timeline

Start: 10-01-2010

Finish: 09-30-2014

75% Complete

DOE Barriers: Cost, Durability & Performance

DOE Targets: H_2 production from biomass-derived renewable liquids <$2.30/gge; Distributed power demo 2Q 2018

Year	Cost/kW	Efficiency	CHP Effic.	Lifetime	Technology
2015	$1700	42.5%	87.5%	40,000h	5 kW Dist Gen
2020	$1500	>45%	90%	60,000h	5 kW Dist Gen

Budget

Total: $2.3M

Received FY13: $667K

Expected FY 13: $559K

Partners/Collaborators

Topsoe Fuel Cell - SOFC

Impact Washington - Commercialization

Mid-Columbia Energy Initiative -- Demo

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Relevance: Project Objectives

Year	Objective	DOE Barriers Addressed
2011 Complete	Establish design to meet technical and operational needs for distributed energy production from renewable fuels	SOFC power using renewable non-food biomass fuel; codes & standards
2011/ 2012 Complete	Design, optimize, and integrate proprietary steam reformer components and balance-of-plant in a highly efficient design.	Demonstration; system efficiency >40%; design for low cost manufacturing
2013/ 2014 In progress	Demonstrate the technical and commercial potential of the technology for energy production, emissions reduction, and process economics	• 40,000 h lifetime • 99% availability • 42.5% efficiency; 87.5% CHP • $1700/kW equipment cost

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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 addresses these issues by focusing on steam reforming fuel processing technology:

- **Helping shift the primary energy source for H_2 from fossil fuels to renewable non-food biomass, using natural gas as the bridge. Added multi-fuel capacity.**
- **Using less fuel through high system efficiency (>42%) by effective thermal integration and off-gas recycling. Added CHP capacity.**
- **Reducing fuel processor equipment cost by lowering NRE through use of additive manufacturing (3-D printing)**

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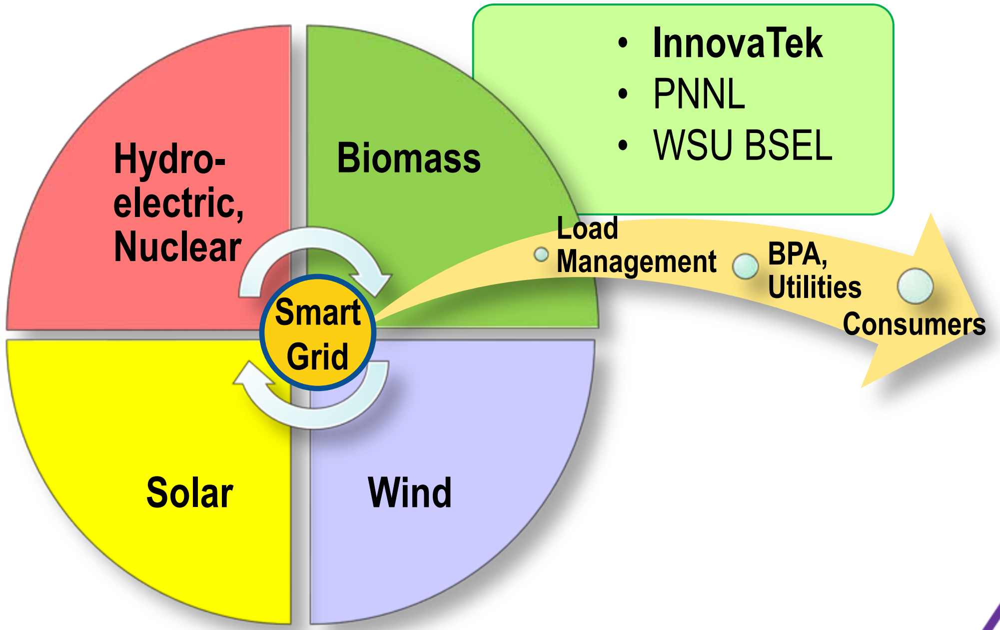
Approach: Project Goal

Develop and demonstrate a fuel cell distributed energy system that operates with 2nd 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

Date	Milestone or Go/No Go	Status
Dec 2013	Go/No Go: Analysis of process economics supports commercial feasibility (Cost of power is competitive)	Markets & Strategic Plan Identified
Jan 2014	M4: Achieve >40% system operating efficiency with revised/optimized system design	42% Efficiency
Feb 2014	M5: System performance proves superior energy efficiency & emissions reductions compared to conventional technology	CHP > 76% Efficiency
March 2014	Complete fabrication of Gen3 prototype for field demonstration; estimate unit costs	Complete; $1,722/kW for 5kW
Sept 2014	M6: Complete 6 months of demonstration and complete economic analysis	In Progress $0.096/kWh

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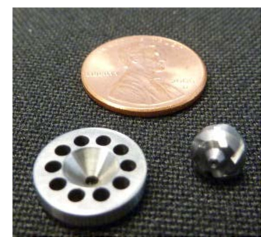
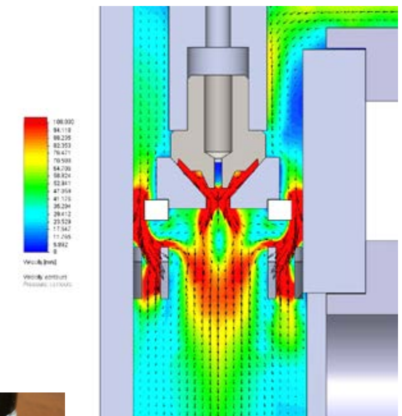
Approach: Fuel Processor Innovations

Targeted Three Areas in this Reporting Period

Addresses lifetime, efficiency, and cost objectives

1. **Multi-Fuel Burner**
   - Cleanly combusts liquid and gaseous fuel for start up & adds anode off-gas after start-up
   - Field swappable nozzles





2. **Multi-Fuel Atomizing Injector**
   - Enhances mixing of fuel & steam
   - Prevents coke & enhances reactant distribution

3. **Catalyst Substrate**
   - High surface area metallic support
   - Resists sintering & crumbling
   - Conforms to reactor geometry & facilitate thermal exchange & reactant mixing

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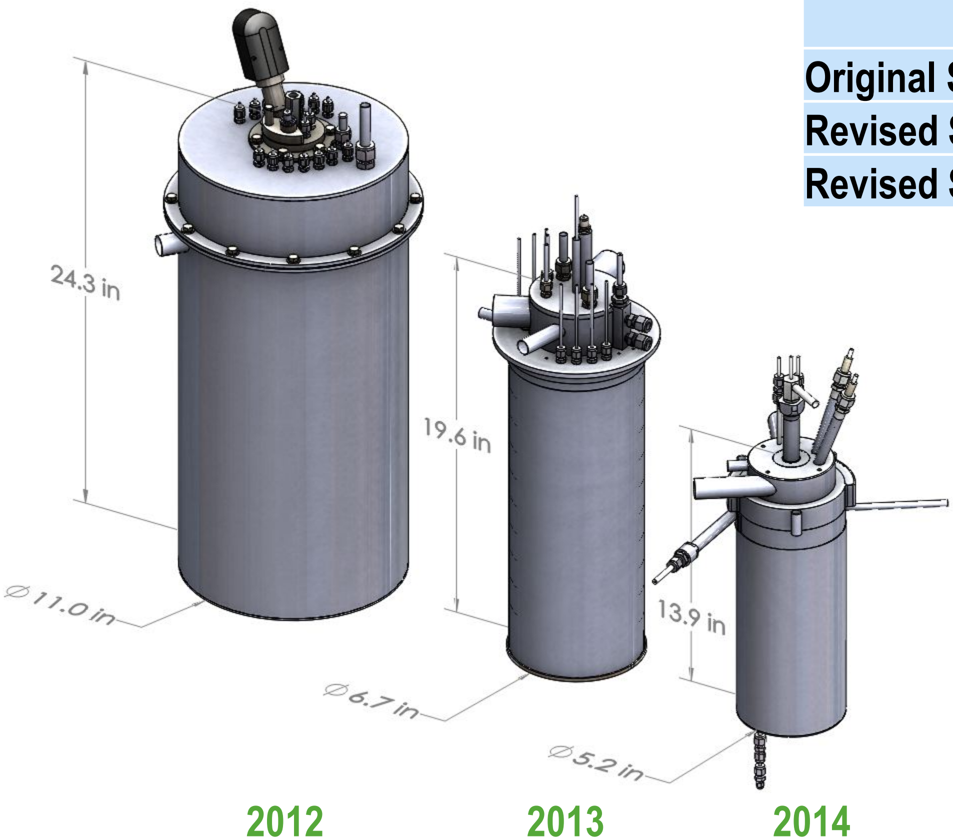
Approach: Manufacturing Innovations

Reduced part count and complexity – Addresses equipment cost objective



	Parts Count	Volume (L)
Original System (Gen 1)	159	37.8
Revised System (Gen 2)	66	11.3
Revised System (Gen 3)	59	4.8

3rd Generation Fuel Processor

57% Size Reduction from previous generation (87% from Gen 1)

- 11% Part Count Reduction from previous generation (63% from Gen 1)
- Volume manufacturing cost of $1722/kW for 5kW integrated system (with fuel cell & BOP) is very close to DOE 2015 goal of $1700/kW

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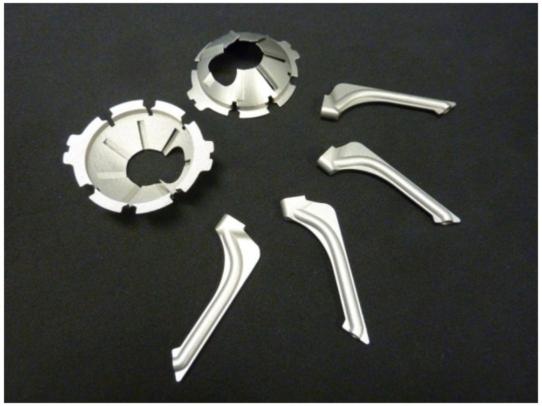
Approach: e-Manufacturing Innovations

Manufactured Parts using 3-D Printing – Addresses equipment cost objective

Direct Metal Laser Sintering

- Uses 3-D CAD files for tool-less production of prototypes
- Fuses high temperature metal powder for functional testing
- Impossible to create same geometry by any other means
- Helped achieve optimal design for prototype



- Produces prototypes quickly and less expensively – reduces NRE costs
- Parts can be stamp formed for mass production

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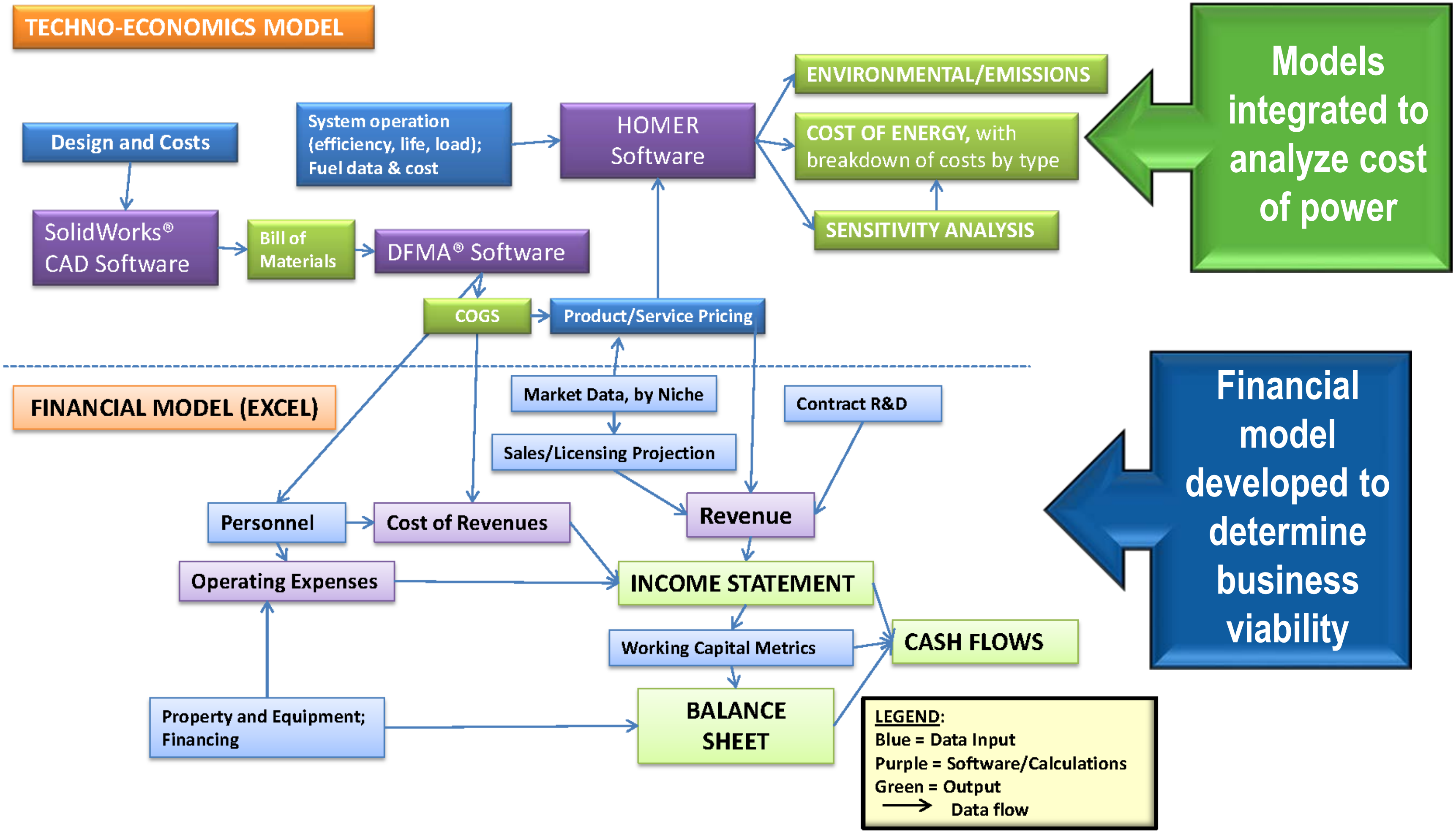
Approach: Economic Analysis



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Accomplishments: Developed Highly Efficient Thermally Integrated System Design

Process Flow Diagram

- Subdivided into 24 process streams

Mass and Energy Balance

- Completed for each process stream
- Determines input, output, efficiency

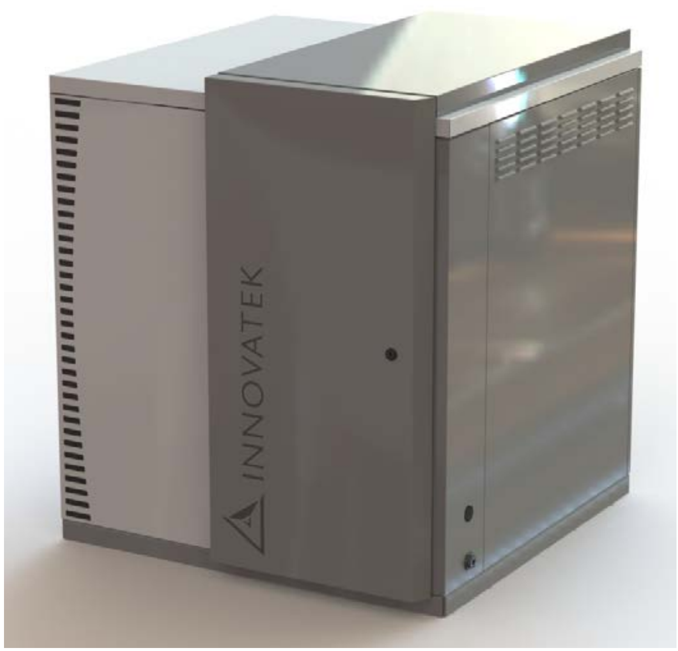
Optimized Layout, Piping & Instrumentation

Solid Model of Integrated System

Milestone 3

Component Design and Analysis

- Process simulations
- Design trade-off analyses



1.3 kW fuel cell system that operates on liquid bio-fuel and natural gas

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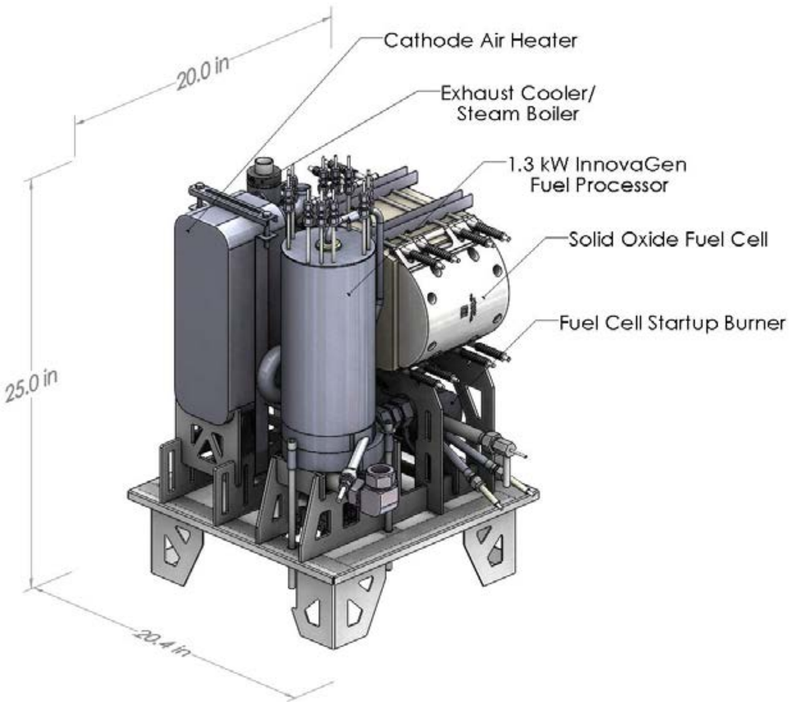
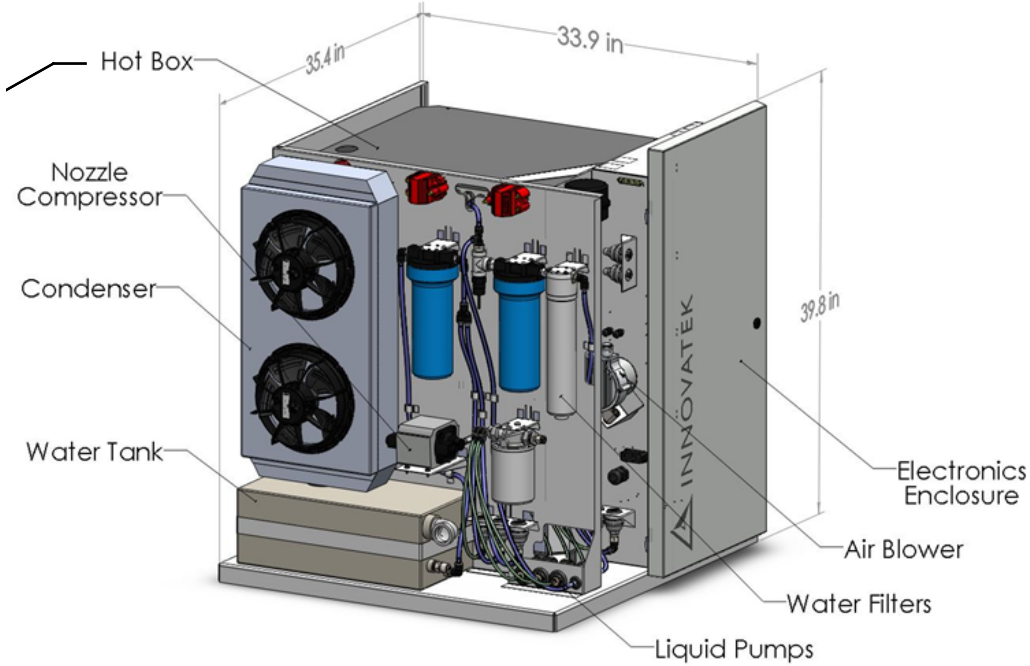
Accomplishments: System Solid Model

Design includes complete Bill of Materials and P&ID



Hot Box Subassembly



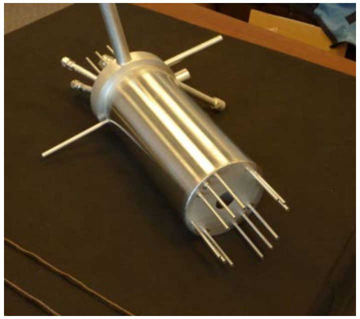
Fully Integrated System

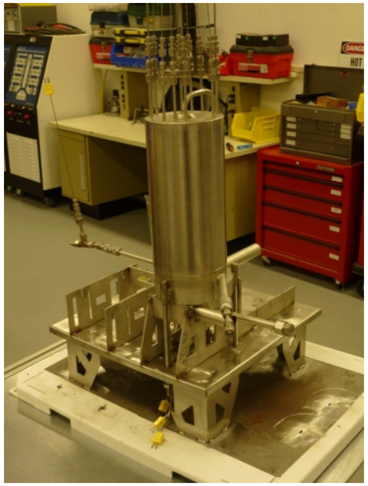
Accomplishments: Manufacture & Assembly

Two Prototype Power Systems Produced

- ✓ Established Bill of Materials to assess equipment costs
- ✓ Worked with manufacturing partners to estimate volume production costs
- ✓ Estimated costs of $1,722/kW for 50,000 units/year for 5kW multi-fuel system

$1,700 = DOE Cost Objective



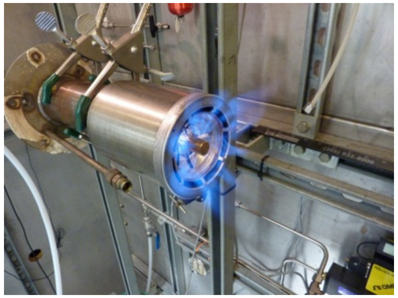


Established manufacturing partners for production of proprietary components

Component Testing Conducted

Burner optimized for natural gas and bio-kerosene combustion

- Determined critical aspects such as air and natural gas flow rate, flame retention head orientation, air introduction location, air flow rate, gas orifice size and gas orifice configuration



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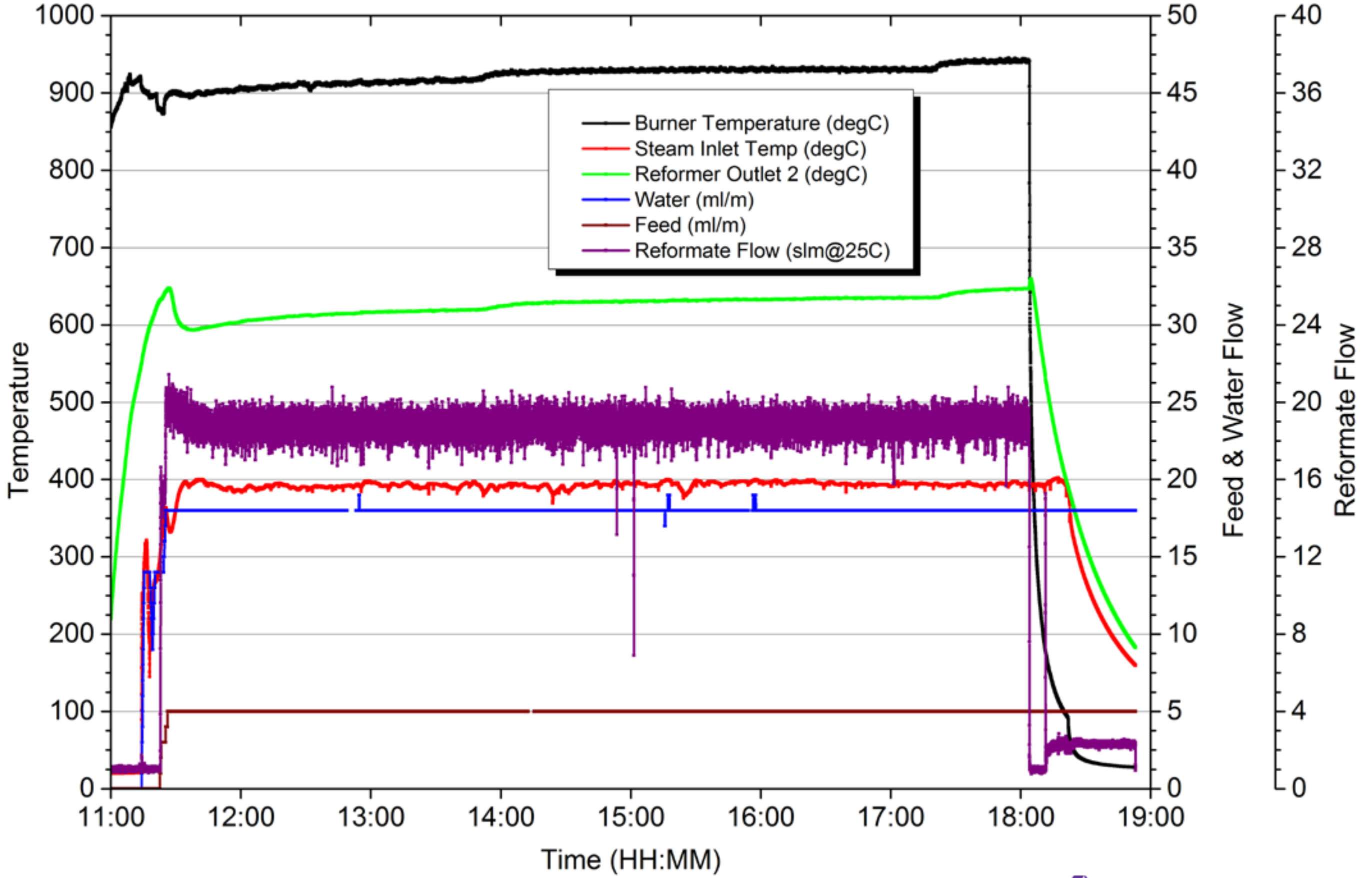
Accomplishments: Performance Data

Reformer operating conditions for bio-kerosene



Gas space velocity = 935/hr

Steam:carbon = 4:1

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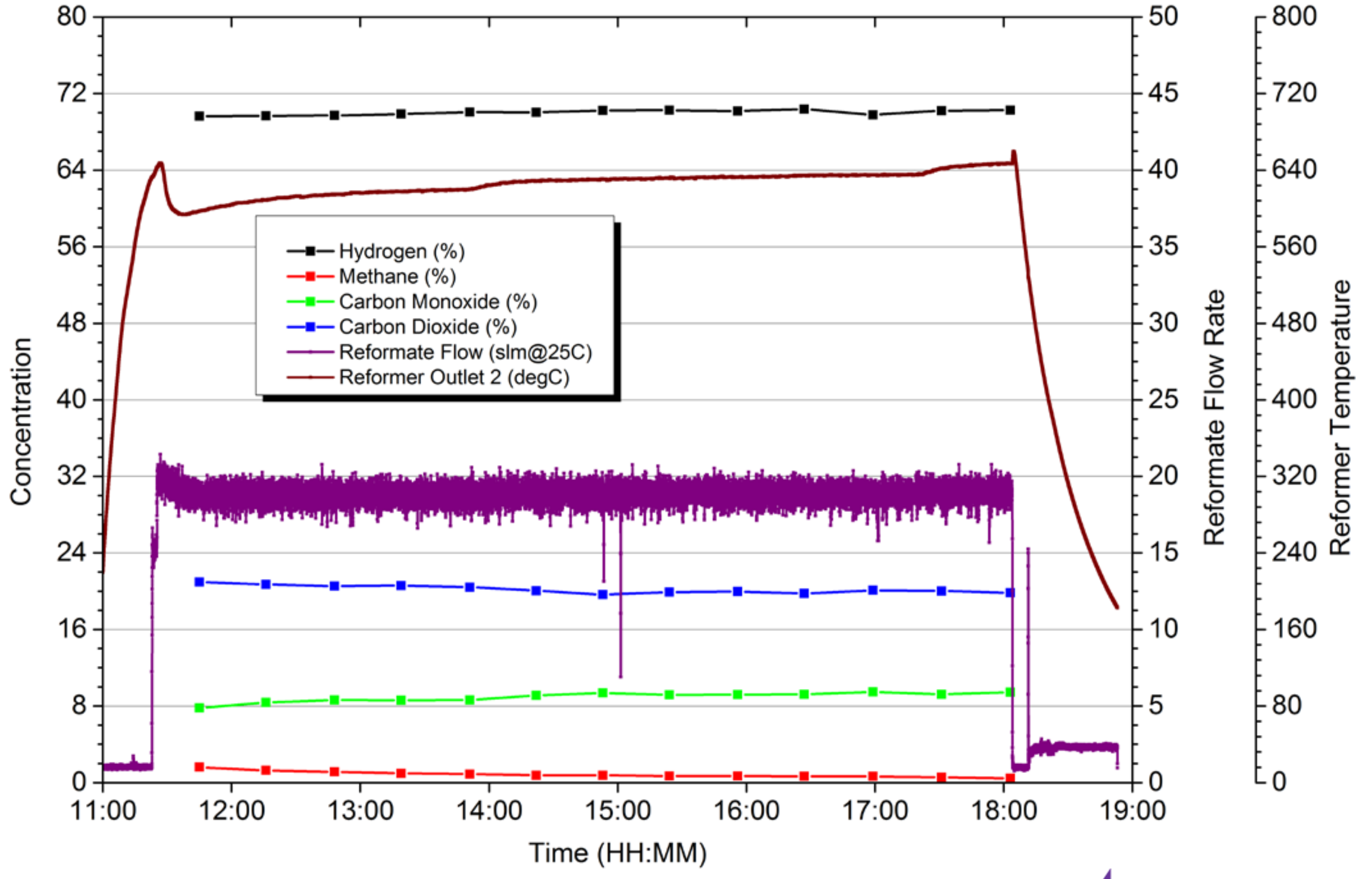
Accomplishments: Performance Data

Reformer product flow rate & composition for bio-kerosene



Gas space velocity = 935/hr

Steam:carbon = 4:1

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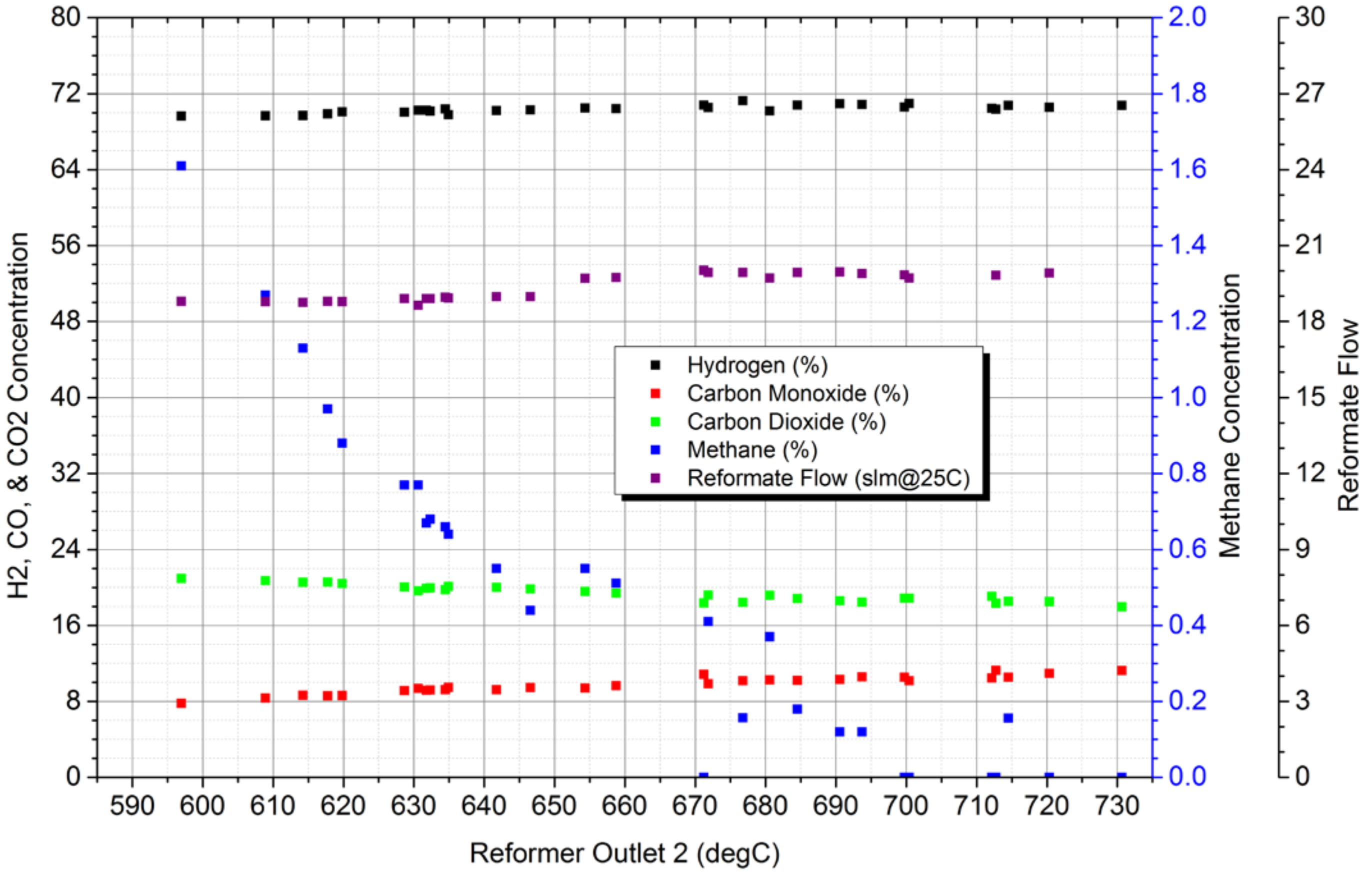
Accomplishments: Performance Data

Reformer product composition & flow rate versus reaction temperature for bio-kerosene



Methane decreases as a function of temperature; Maximum reformate flow rate at ~670°C

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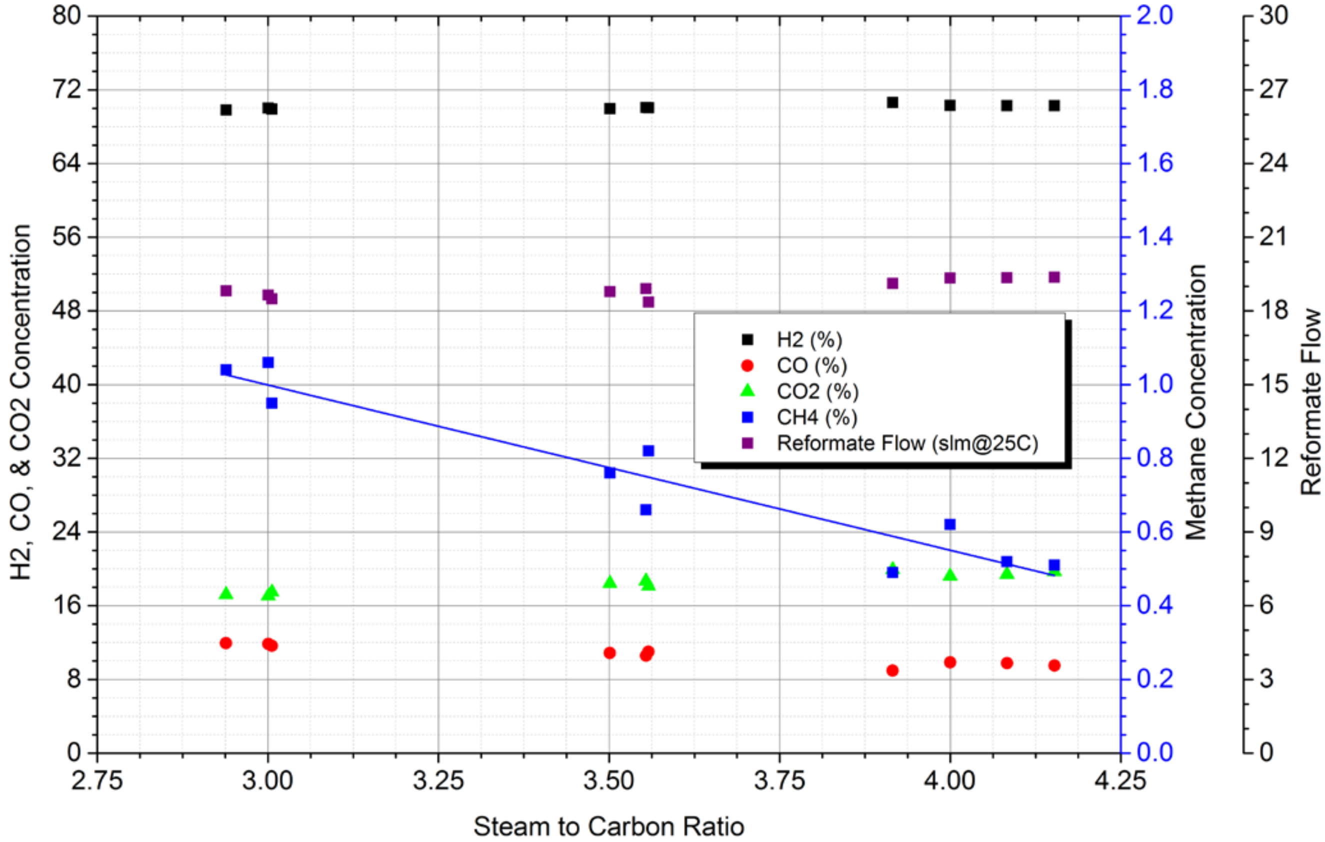
Accomplishments: Performance Data

Effect of steam:carbon ratio on bio-kerosene reforming



Gas space velocity = 935/hr

Reforming temp = 680°C

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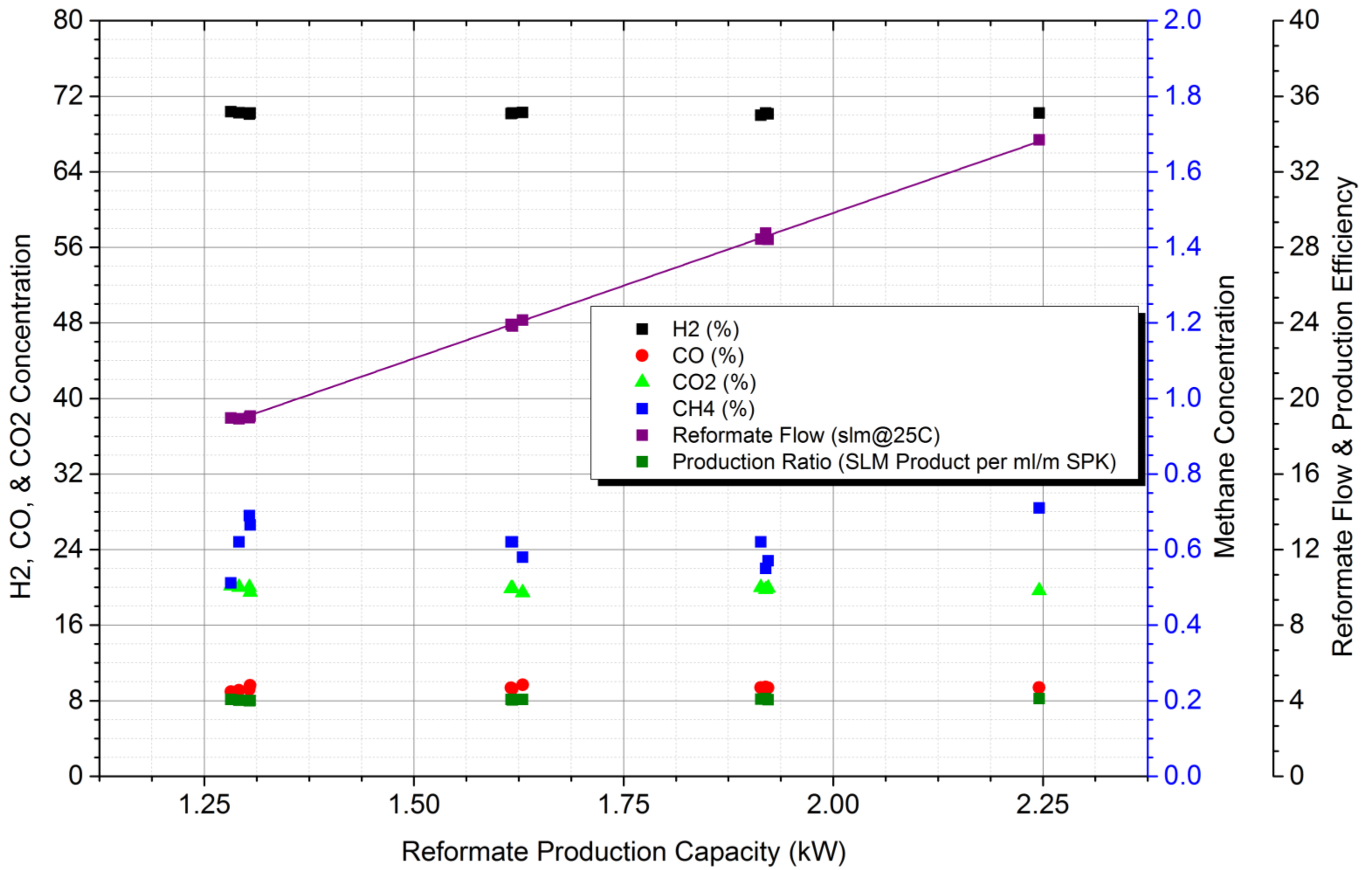
Accomplishments: Performance Data

Effect of feed rate on bio-kerosene reforming



Steam:carbon = 4:1

Reforming Temp = 680°C

Max gas space velocity =1636/hr

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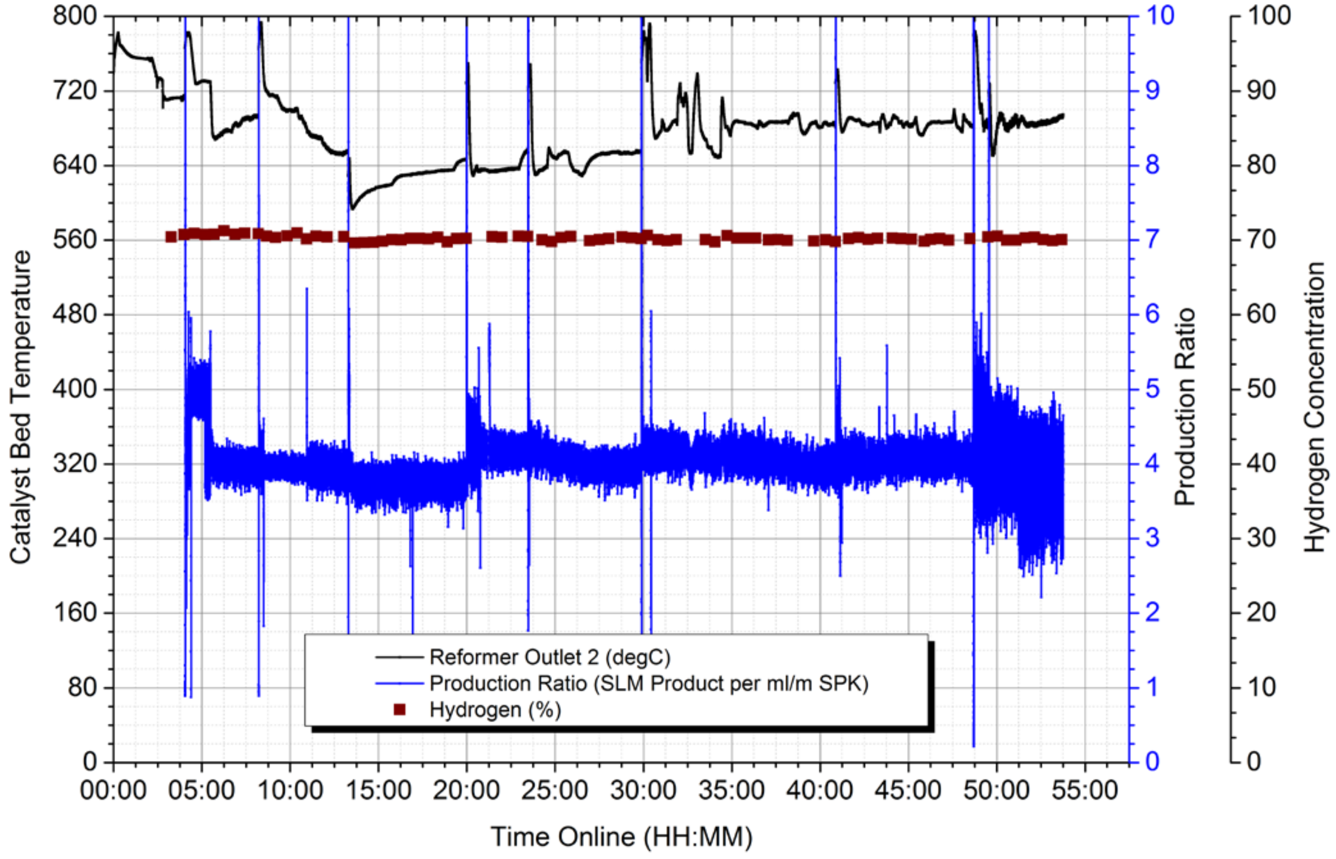
Accomplishments: Performance Data

Time on stream reforming bio-kerosene with 9 thermal cycles



Thousand hour test is continuing

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Accomplishments: 42-76% System Efficiency

Current density, mA/cm^2	200
Cell active area, cm^2	144
Stack current, A	28.8
Cell voltage, volt	0.92
Number of cells	50
FC Operating Temp	800°C
gross DC power, watt	1321
stack electrical efficiency (LHV)	73.2%
parasitic power, watts	195

Fuel Type	Liquid	Gas
Net AC electrical efficiency	41.9%	42.3%
Thermal Efficiency	31.2%	34.1%
System (CHP) Efficiency	73.1%	76.4%

Improved from last year (41%) due to:

- Better stack efficiency
- Addition of heat exchanger for CHP

Calculations based on modeling results for current system design and fuel processing system performance results

Nearly meets DOE 2015 goal 42.5%

Approaches DOE 2015 goal 87.5%

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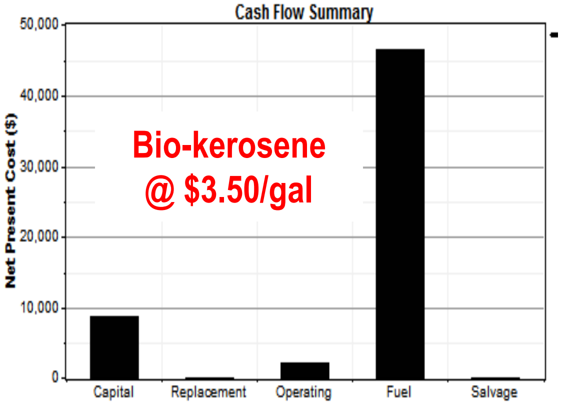
Accomplishments: Economic Analysis

Updated cost of energy analysis found that:

1. Our 5kW fuel cell generator operating on natural gas would be competitive ($0.096/kWh) when volume production brings capital costs down.
2. Price for liquid bio-fuel, at $3.50/gal, is dominant factor affecting cost of electricity when operating on bio-fuel.



In response to these analyses, this year we:

- Adapted our fuel processor to reform both natural gas and liquid bio-fuels and added a heat exchanger for CHP applications;
- But, until there is a large scale market for small residential distributed energy, the technology is not economically viable.

Therefore we also:

- Surveyed the marketplace for currently viable early adopters
- Developed a go-to-market strategy for those applications

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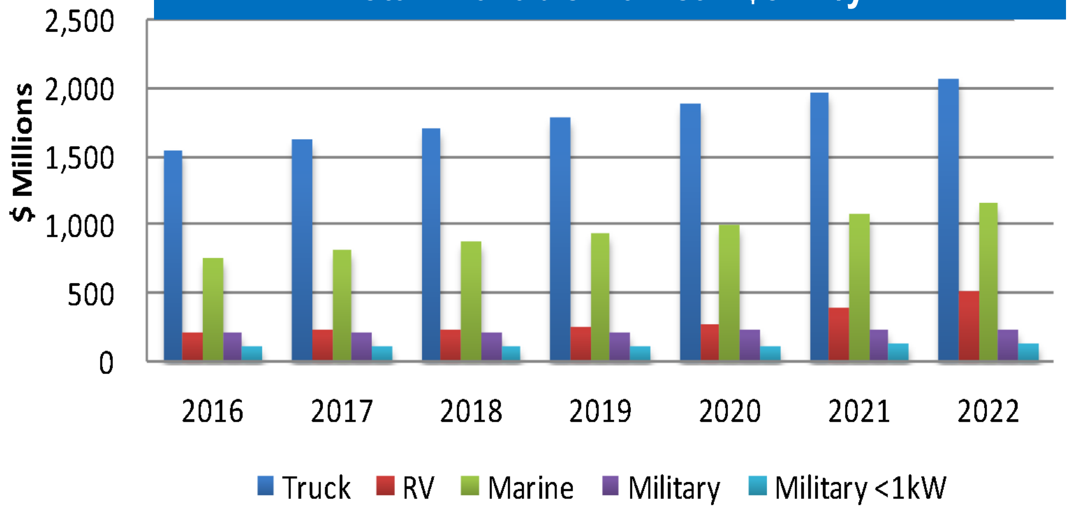
Accomplishments: Markets and Strategy

- ✓ Initial markets identified
- ✓ 3-year strategic action plan in place
- ✓ Established relationship with commercial partners
  - Ingersoll-Rand - truck APU
  - Northern Lights - marine APU
  - Bren-Tronics - military power

Total Available Market = $3.4B/yr



InnovaGen® Prototype APU

Prototype Soldier Power

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Collaborations

Subcontractors

- Topsoe – SOFC
- Manufacturing partners – 3-D Printing (Direct Metal Laser Sintering)

Strategic Partners

- Impact Washington – commercialization strategy support
- PNNL – provided upgraded bio-oil made from non-food biomass (within DOE H_2 Program)
- Honeywell UOP – provides bio-kerosene
- Systems Integrators – working with several commercialization partners for identified markets
- Mid-Columbia Energy Initiative – collaboration for demonstration

Education

- Supported 1 graduate student from WSU and 1 Delta HS intern in mechanical engineering and chemistry

Future Work

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

- Continue long term performance tests of fuel processor with both bio-fuel and natural gas to obtain durability data
- Obtain performance data for multiple fuel processors
- Integrate balance of plant and fuel cell
- Verify performance and durability with long term and accelerated stress testing
- Further analyze process economics and market strategy
- Continue collaborations and establish additional relationships with fuel cell partners and systems integrators for the markets identified
- Conduct additional Phase III projects for APU applications with HTPEM (beyond this project)

Response to 2013 Reviewer Comments

More focus on system operating characteristics, performance, durability and identifying expected maintenance schedule, cost, and operational availability

- See Slides 4-20, 24, 28, 36, 37

Omissions in critical information regarding technology and method of operation

- See Slides 14, 19, 20, 34

Methane yield in reformer is high

- Reforming temperature increased to reduce methane to <1%, See Slide 16

More information on how system is to be used

- As a distributed power system with 24/7 operation (Slide 30 & 34), or integrated with a PEMFC for use as an APU with intermittent operation (Slide 29)

Defer field demo and study performance and durability of component in the laboratory

- Will concentrate on laboratory performance studies, see slide 24

Develop additional partnerships for system integration and with FCE for SOFC.

- Promising discussions were held with Versa and then with FC Energy after their acquisition; however, FC Energy says it is not producing systems in our size range and cannot effectively integrate with our system at this time; Currently interacting with other U.S. FC Companies

Summary

Relevance: Shift energy from fossil to renewable fuels; improve performance, lower costs

- 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 demonstration and economic analysis

Accomplishments: Achieved 42% system efficiency, 76% CHP efficiency, $1,722/kW

- 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 2 students; Subcontractors for fuel cell & manufacturers;

- Partnerships with PNNL, WSU, Boeing , City of Richland, Regional Energy Initiative

Future: Complete performance analysis with multiple 1.3 kW prototypes

- Complete durability testing of fuel processor, integrate SOFC & continue testing
- Further analysis of process economics and collaboration with systems integrators

Technical Back-up

Technical: System Efficiency Algorithms

system efficiency (electrical efficiency)

$P_{parasitic} := 300W$

regulated DC power

$$DC_{reg}(I_d) := DC_{gross}(I_d) \cdot \eta_{dc\_dc}$$

net DC power

$$DC_{net}(I_d) := DC_{reg}(I_d) - P_{parasitic}$$

net AC power

$$AC_{net}(I_d) := DC_{net}(I_d) \cdot \eta_{dc\_ac}$$

$$\eta_{ele} := \frac{AC_{net}(I_d)}{LHV_{spk} \cdot (n_{feed} + n2) \cdot MW_{spk}} = 40.793 \cdot \%$$

$\eta_{ele} = 0.408$

$DC_{gross}(I_d) = 4.221 \times 10^3\ W$

$\eta_{dc\_dc} := 95\%$

$\eta_{dc\_ac} := 92\%$

$OCV_{HHV} := 1.48volt$

$OCV_{LHV} := 1.25volt$

$$\eta_{volt} := \frac{Volt800_{cell}}{OCV_{LHV}} = 0.656$$

$$\eta_{fps} := \frac{LHV_{h2} \cdot N_{anode\_in_3} + LHV_{ch4} \cdot N_{anode\_in_0} + LHV_{co} \cdot N_{anode\_in_1}}{LHV_{spk} \cdot (n_{feed} + n2) \cdot MW_{spk}} = 112.977 \cdot \%$$

Back-up: Strategy Analysis

Early adopter markets were evaluated that have:

- ✓ Best alignment with InnovaTek's existing technology development achievements, program funding, & size, weight and cost profile;
- ✓ Favorable economics and market drivers; and
- ✓ Market timing that aligns with product maturation timeline

- 5 markets selected as candidates (with PEMFC because of thermal cycling)
  - Auxiliary Power Units (APUs): Truck, Marine, RV
  - Military: Soldier Portable Power (<1kW), APUs (>1kW)
- Stationary market not currently competitive due to product cost at low volumes and to low price of natural gas as feedstock

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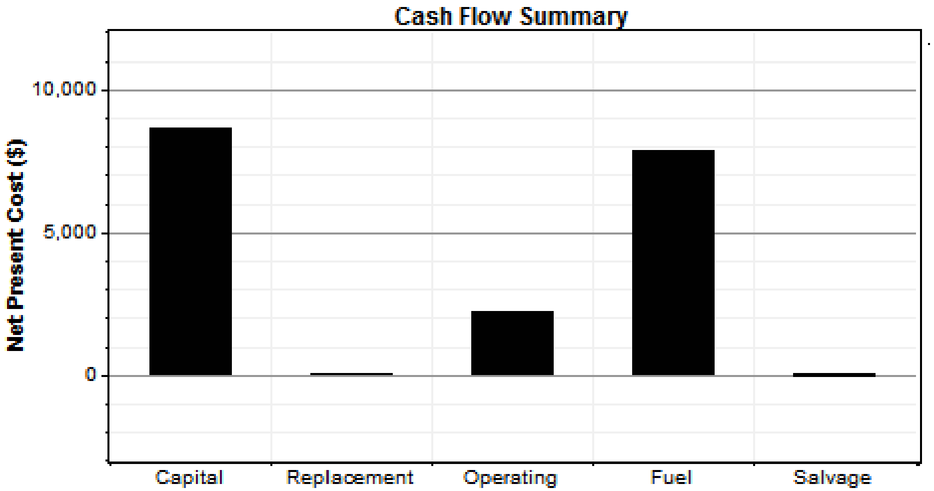
Back-up: Cost of Energy Model

5kW Natural Gas Distributed Energy System

Cost summary

Total net present cost	$ 18,407
Levelized cost of energy	$ 0.096/kWh
Operating cost	$ 2,241/yr



	Capital	O&M	Fuel	Salvage	Total
Net Present Costs, $	8,610	2,223	7,827	-70	18,590
Annualized Costs, $/yr	1,970	509	1,791	-16	4,253

Assumptions:

Natural gas price (current spot price)	0.168 $/m^3
Lifetime	5 yrs
Hours of operation	8,760 hr/yr
Starts/yr	1
Interest rate	4%

Levelized cost of energy of $0.096/kWh is competitive

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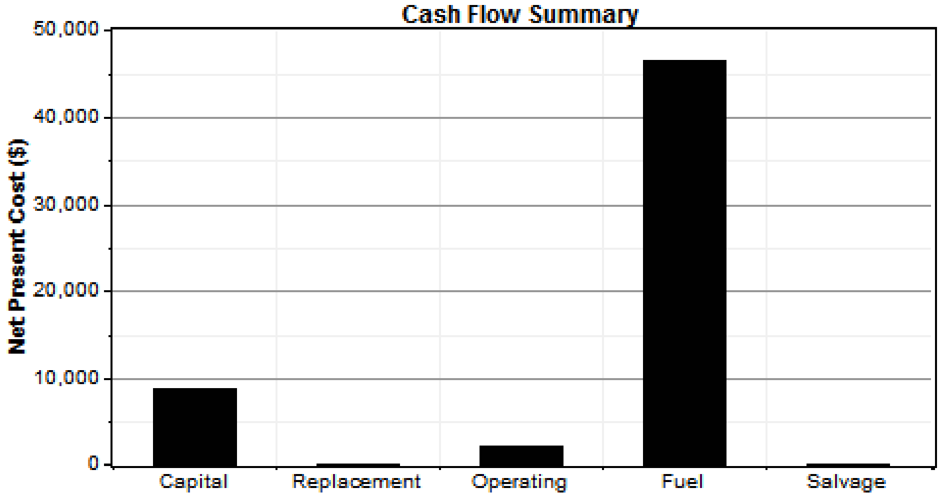
Back-up: Cost of Energy Model

5kW Bio-Kerosene Distributed Energy System

Cost summary

Total net present cost	$ 56,797
Levelized cost of energy	$ 0.294/kWh
Operating cost	$ 10,923/yr



Assumptions:

Bio-Kerosene price	$3.50/gal
Lifetime	5 yrs
Hours of operation	8,760 hr/yr
Starts/yr	1
Interest rate	4%

Levelized cost of energy of $0.294/kWh is not competitive without carbon tax or other incentives

	Capital	O&M	Fuel	Salvage	Total
Net Present Costs, $	8,610	2,223	46,403	2	57,237
Annualized Costs, $/yr	1,952	504	10,519	0	12,975

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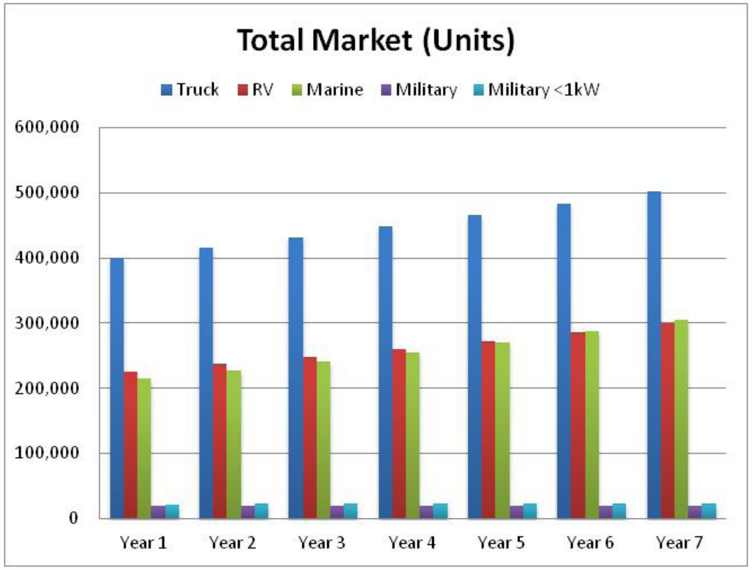
Back-up: Financial Model

Dynamic Excel based financial spreadsheet tool, featuring:

- Up to 5 independently timed and characterized markets for up to 7 forecast years
- Markets characterized for overall and our addressable share
- Revenue models include sales, lease, and licensing
- Scenario modeling driven by tables of key variable values



➢ **Output includes financial statements, charts, and investment return**