Final Scientific Report

Low-cost Co-production of Hydrogen and Electricity

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Contract Number: DE-FC36-0515195

Subcontractors:
University of Alaska, Fairbanks, Alaska
Udelhoven Oilfield System Services, Anchorage, Alaska

Vendor:
H2 Pump LLC, Latham, New York
Giner Electrochemical Systems LLC, Newton, Massachusetts

Project Start Date: November 13, 2006

Project End Date: June 30, 2010

Date of Report: September 28, 2010

Executive Summary

The purpose of this study is to further the efforts of low-cost co-production of hydrogen and electricity. Hydrogen price parity with gasoline is an imperative if hydrogen is to be used for transportation fuel. A distributed, rather than centralized, generation approach to hydrogen production avoids infrastructure costs and allows for safer and more convenient distribution to customers.

Bloom Energy's (BE's) systems, when manufactured in high volume, can produce low cost hydrogen by co-producing hydrogen and electricity simultaneously with one common set of low-cost equipment. The main objectives of this project have been to 1) deliver and field test a pilot plant producing high purity hydrogen and electricity in Alaska; 2) show the feasibility of a delivered cost of hydrogen below $2.50 per gge; 3) demonstrate that our systems can run on liquid fuels; and 4) create learning opportunities regarding commercial customer needs so that the DOE and BE can use this demonstration project to gain critical insights necessary to build, deliver and install a commercially viable stationary fuel cell-based hydrogen/electricity co-production system.

Over the course of this project, BE has successfully demonstrated the ability to build and operate a PSOFC for 12 months, with a peak efficiency over 50%, while improving the understanding of operating requirements in cold weather. BE also demonstrated the capability to co-produce electricity and hydrogen, and to generate pure hydrogen in volumes of 19.3 kg/day; and additionally demonstrated the feasibility of a delivered cost of hydrogen below $2.50 per gge

Objectives

- Demonstrate efficient, reliable and durable solid oxide fuel cells for stationary applications
- Demonstrate co-production of electricity and hydrogen
- Determine the feasibility of a delivered cost of hydrogen below $2.50 per gge by 2010

Accomplishments

2008:
- Complete site construction
- Install, commission & begin remote operation of PSOFC system
- Hydrogen pump production system build, test & optimization
- Combined PSOFC & hydrogen production system testing
- Partial pressure swing adsorption (PPSA) prototype design
- Begin hydrogen cost analysis using the DOE H2A model

2009:
- Complete PSOFC system demonstration
- Complete hydrogen production demonstration
- Begin PPSA build, test & investigation
- Complete hydrogen cost and economics analysis

2010:
- Complete H2 pump stack tear down analysis
- Complete PPSA build and initial testing
- Decommission site

Approach

The project was divided into two phases. Phase 1 included the build of a PSOFC electricity generator; the design, permitting and build of a demonstration site; and the installation, commissioning and start up of the generator. This phase also includes evaluation of several hydrogen production technologies for integration and validation with a lab-based PSOFC.

Phase 2 covered the one year demonstration of the PSOFC electricity generator. It also included the build, test and demonstration of the hydrogen generation sub-system, as well as the delivered cost of hydrogen, using the DoE's H2A model. More specifically, the following was included:

- Test a vendor provided hydrogen pump prototype in stand alone mode
- Analyze the volume and purity of hydrogen produced by prototype unit
- Design the integration of the vendor provided hydrogen pump production unit with our PSOFC system
- At our Moffett Field site, test the hydrogen pump integrated with our PSOFC system
- Analyze the volume and purity of hydrogen produced
- Operate the PSOFC system in the field for twelve months
- Analyze the efficiency and availability of the fuel cell
- Analyze the results of PSOFC electricity and hydrogen co-production

Fuel Cell Demonstration

The fuel cell demonstration site in Anchorage, Alaska was designed and permitted in Q1, 2008. Construction completion and operational permitting occurred in October, 2008. Two 25kW PSOFC modules were installed, commissioned and started up in November, 2008. Approval to grid connect was provided on December 1, 2008. System demonstration objectives were projected as follows:

- 25 kW power
- Operation on natural gas
- Operate at 480V
- Grid parallel operation
- Remote monitoring
- 70% uptime over one year demonstration
- 45% peak net electric efficiency in electric-only mode

The following performance metrics were demonstrated for the one year period, ending December 2, 2009:

Power Module 1C: 12/3/08-12/2/09		
Average AC Efficiency	41.4	%
Total Energy Output	153,474	kWhrs
Total Fuel Consumption	36,989,143	L
Peak AC Power	25.9	kW
Peak AC Efficiency	51.1	%
Hrs On-Site	8743	Hrs
Uptime	8721	Hrs
Load Hrs	8509	Hrs
Grid Faults	10	
System Faults	7	

Figure 1: Power Module 1C Performance Summary

Power Module 1D: 12/3/08-12/2/09		
Average AC Efficiency	43.5	%
Total Energy Output	161,716	kWhrs
Total Fuel Consumption	37,129,950	L
Peak AC Power	25.4	kW
Peak AC Efficiency	49.1	%
Hrs On-Site	8743	Hrs
Uptime	8706	Hrs
Load Hrs	8414	Hrs
Grid Faults	9	
System Faults	8	

Figure 2: Power Module 1D Performance Summary

All of the above objectives were achieved or exceeded. Uptime percentage over the one year demonstration was 99.7% and 99.6%, respectively for power modules 1C and 1D, exceeding the 70% target. Peak AC efficiency was 51.1% and 49.1%, respectively for power modules 1C and

1D. The peak AC power was 25.9kW and 25.4kW, respectively. The systems were purposefully operated at lower power to validate operational endurance.

Nine total service calls were required during the demonstration period, with the primary fault condition being site weather conditions. Replacement of the water pump and water flow meter was required, as they were not rated for conditions below 0 degrees Celsius. Additionally, hoarfrost clogged the building air intake, resulting in the shutdown of the building's thermal control, leading to system fault. Other common faults experienced were due to grid faults, or to typical maintenance.

The following components were upgraded during the course of operation as a result of fault conditions:

- Power electronics – inverter
- I/O boards
- Mass flow controller
- Anode recycle blower

Additional research and development was done with the air blower vendor to reduce parasitic losses and simplify installation. Starting with a commercially-available air blower, we used computational fluid dynamics to develop a series of modifications to make it suitable for operation as an anode recycle blower capable of high temperature ambient/media:

- Hydrogen
- Carbon Dioxide
- Steam
- Carbon Monoxide

Due to the system's location and the time of year, cold weather testing was performed on the system after the one year demonstration period ended on December 2, 2009. The objectives of this testing were to verify the system operation at temperatures from (0°C to -20°C). Water lines were insulated and multi-stranded resistance wire (heat trace) was installed in some locations. Thermocouples were mounted on key components, and the system was tested at various temperatures and power settings. Determinations were made to increase insulation or activate resistance heating elements, as deemed necessary in the field. Results of testing indicate that the system, when kitted especially for cold weather, can operate through periodic sub-0°C temperatures. Temperatures below this level require increased insulation, robust heat trace methods, and management of water within the system.

The fuel cell system was powered down, following cold weather testing, on February 28, 2010.

Hydrogen Production Demonstration

A hydrogen pump from H2 Pump, LLC of Latham, New York was chosen as the demonstration vehicle for the H2 production portion of the project. A small scale H2 Pump product was validated at Bloom Energy's laboratories and demonstrated that H2 pumping: 1) is scalable; 2) has high electrochemical efficiency (low power required/kg H2) ~$0.12/kg H2 @ $0.10/kW-hr electrical costs; 3) is a continuous flow device having a near infinite turn down ratio with minimal parasitics when not pumping hydrogen; and 4) can pump hydrogen on demand.

A 120-cell H2 pump was procured and designed for integration to a 25kW PSOFC (see Figure 3). In September 2009, the H2 pump, coupled to an SOFC system sited at Moffett Field, CA, was brought up and commissioned. The pump began operation with SOFC in hydrogen recycle mode; the hydrogen produced is recycled back to the fuel inlet of the SOFC. Hydrogen production was shown to be linear and in line with expectation as shown in Figure 4. :

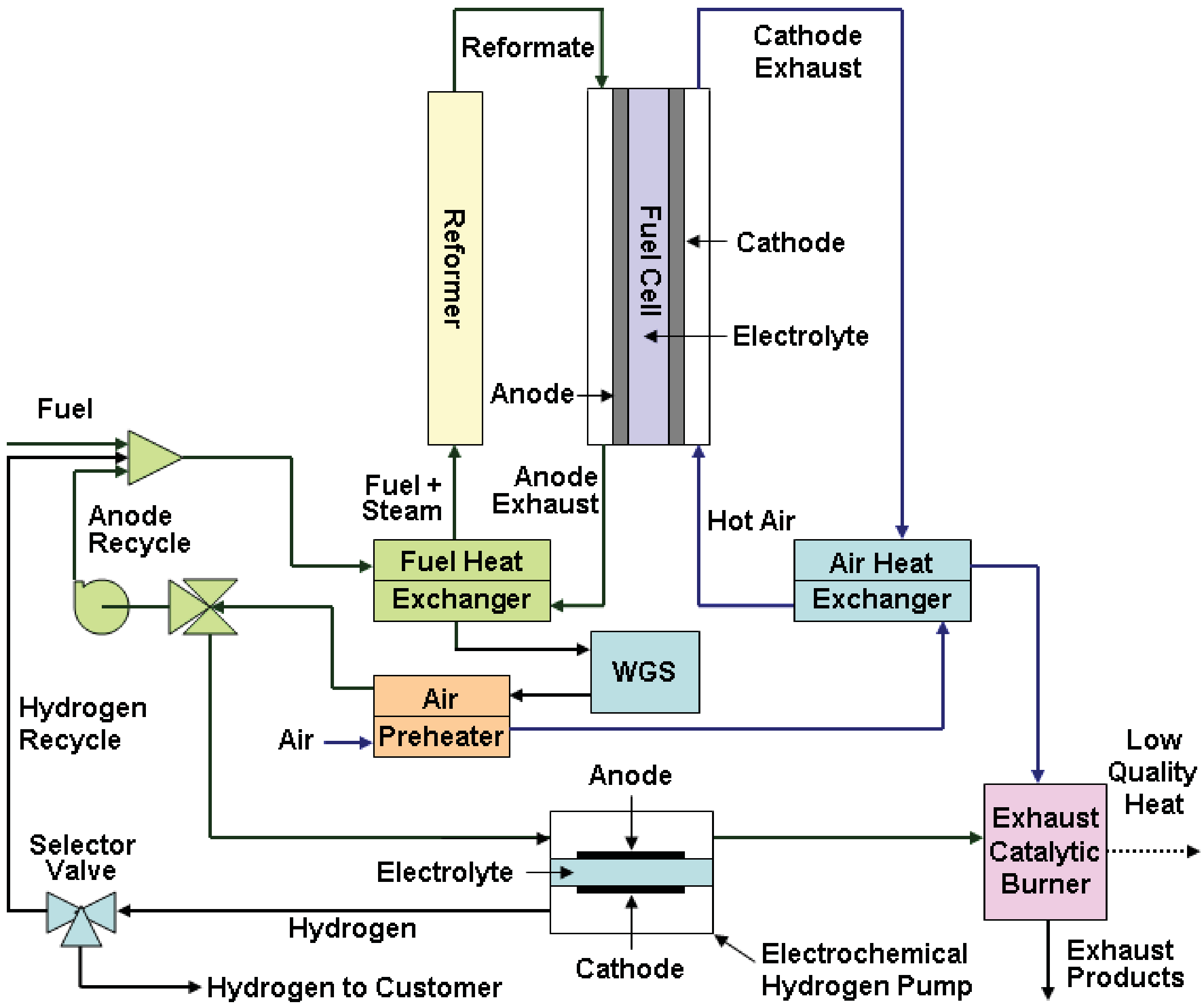

Figure 3: Integrated SOFC and Hydrogen Pump Fluid Schematic

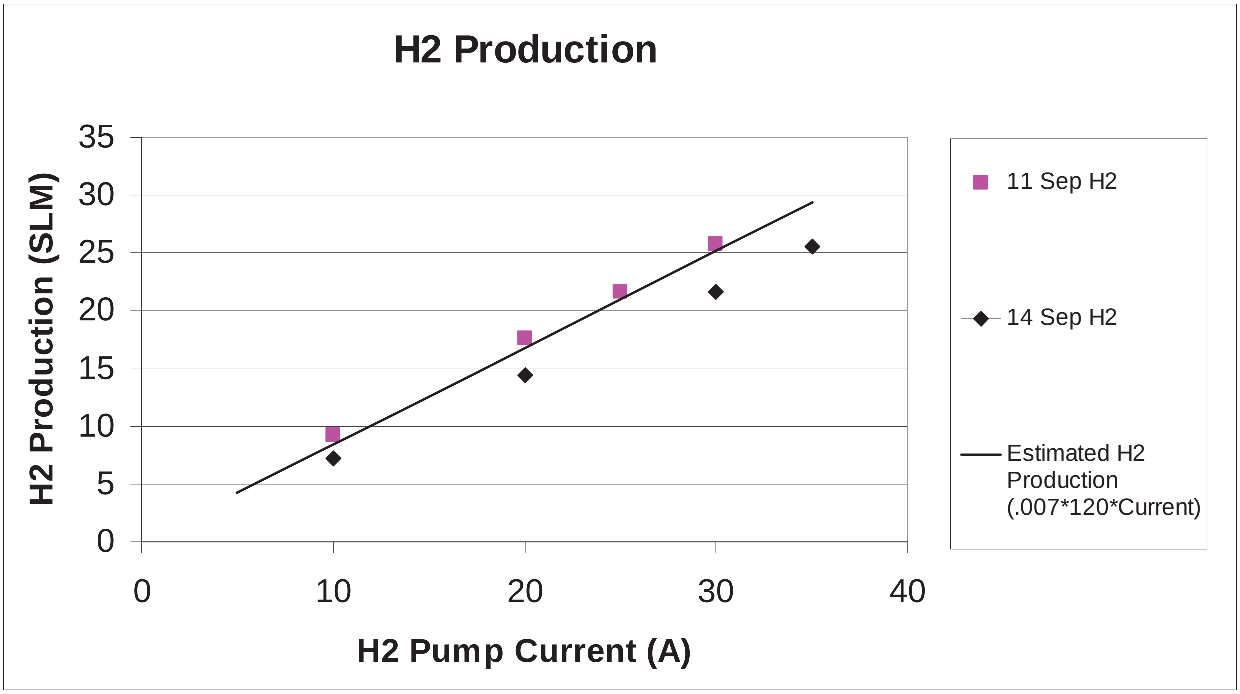

Figure 4: Estimated H2 Production

Baseline efficiency measurements for the SOFC system operating without the H2 Pump were taken over a 1 month period (see Figure 5). The average net SOFC system efficiency (AC power to grid / LHV natural gas) during this period was 47.8%.

A 10-day average performance of the same SOFC system operating with the H2 Pump is shown in Figure 6. The average net SOFC system efficiency taking into account all parasitics was 52.0%. The H2 Pump power consumption at 35A, was 263W. In addition, there was 264W measured for heaters and H2 Pump ancillary components (measured using a power analyzer). The total H2 Pump parasitic power = 263W + 264W = 527W.

Date and Time	9/11/2009 2:10pm	9/15/2009 1:11pm	9/23/2009 1:08pm	9/29/2009 2:14pm	10/05/2009 9:15pm	10/13/2009 6:04pm
Main Fuel Flow [slm]	64.5	64.6	65.4	66.2	64.7	64.5
AC Power [kW]	18.9	18.6	18.7	18.9	18.6	18.6
SOFC Efficiency [%]	**48.4**	**47.7**	**47.5**	**47.4**	**47.8**	**47.8**

Figure 5: Baseline SOFC performance over ~1 month without H2 pumping

	SOFC with H2 Pump Excluding H2 Pump Parasitic Power	SOFC with H2 Pump Including H2 Pump Parasitic Power
Main Fuel Flow [slm]	57.8	57.8
AC Power [kW]	18.4	17.9
SOFC Efficiency [%]	53.5*	**52.0**

* Efficiency excluding power consumed by H_2 Pump assembly, heaters and components

- H2 Pump power consumption at 35A * 7.5V = 263W
- Measured 264W for heaters and H2 Pump ancillary components using power analyzer
- Total H2 Pump parasitic power = 263W + 264W = 527W

Figure 6: 10-day average SOFC performance with H2 Pump in recycle mode

The 120-cell H2 Pump stack successfully completed its 2,000 hour testing plan as discussed above, and was returned to the vendor after 2,000 hours of testing. Operational test results were reviewed, and disassembled components were examined for changes from new component conditions. Results of this analysis indicate that the modest levels of voltage degradation observed during testing were possibly due to the damaging effects of liquid water in the stack, which appeared to have entered the stack from an anode connection

Hydrogen Purification Demonstration– H2 Pump

It was found that the CO and CO_2 content in the product hydrogen from the hydrogen pump were above DOE specification requirements. However, we were able to accomplish goal of producing high purity 19 kg H_2/day (pro rated) using a palladium diffuser in conjunction with a hydrogen pump. We had to increase the H_2 pump current to 120 A instead of the 82.9 A initially estimated in order to achieve this goal because of the bypass bleed required for the palladium diffuser.

Gas sampling was done on the H_2 product both at low and high current settings. Gas chromatograph analysis showed no detectable CO or CO_2 peaks. Detection limits for CO and CO_2 content is less than 1ppm.

Hydrogen Purification Demonstration – PPSA

In addition to the hydrogen pump, a partial pressure swing adsorption (PPSA) prototype was developed and tested. The simple design includes the same basic components as commercial PSA air dryers. Manufacturer's initial testing indicates the following:

- No water gas shift required
- Low parasitic electrical power
- Anode exhaust to be separated:
    - Flow rate: 99 slpm
    - Temperature: 30C
    - Supply pressure: 5 inches water column
    - H_2 (29.3%), CO_2 (66%), H_2O (3.4%) & CO (1.3%)
- PPSA design point:
    - 80% fuel recovery (CO, H_2)
    - 95% CO_2 separation
    - Pressure drop < 5-inches water column

Next steps for PPSA study include:

- Confirm Manufacturer's results in-house
- Study integration challenges with SOFC and current PPSA hardware
- Utilize results to study optimization of current hardware configuration
- Study commercial feasibility of PPSA given compliance requirements

Hydrogen Cost Analysis

The DoE's H2A cost model was used to determine the feasibility of a delivered cost of hydrogen below $2.50 per gge by 2010, as well as the economics of hydrogen and electricity co-production for comparison to stand alone hydrogen production facilities. Shown below, this model is compared to BE's original proposal**:**

	Original Proposal (BE model)	Current Analysis (H2A Model)
Installed Capital Cost	$1,500 / kW	$1,500 / kW
Overall System Efficiency	56%	56%
Net Electrical Efficiency	33%	33%
NG Cost	$8 / mmbtu	AEO 2007
Capacity Factor	90%	98%
H2 / Year	50,192 kg	54,656 kg
Electrical Output	200kW	200kW
Delivered cost of H2/gge	**$4.82**	**$4.53**

Figure 7: Hydrogen cost analysis using the DoE H2A Model

BE and H2A models are very consistent, with differences only in the assumed capacity factor. Adding the value of electricity, projections outlined below are consistent with DOE delivered cost of H2goals:

	Original Proposal (BE model)	Current Analysis (H2A Model)
Delivered cost of H2/gge	$4.82	$4.53
Value of Electricity	$0.12 / kWh	$0.12 / kWh
Electrical output	1,576,800 kWh / year	1,716,960 kWh / year
Value of annual output	($167,360)	($182,240)
H2 / Year	50,192 kg	54,656 kg
Value of Electricity / kg H2	($3.77)	($3.77)
H2 cost, net/gge @ 300 psi	**$1.26**	**$0.97**

Figure 8: Hydrogen cost analysis adding the Value of Electricity

Publications/Presentations

A presentation was made at the DOE Hydrogen Program Annual Merit Review at the following locations/dates:

- Arlington, Virginia on June 10, 2008
- Crystal City, Virginia in May, 2009

Acronyms

BE – Bloom Energy
gge – gallon of gasoline equivalent
PSOFC – Planar Solid Oxide Fuel Cell
ppm – part per million
DOE – Department of Energy
psig – Pounds per square inch gauge
SOFC – Solid Oxide Fuel Cell

Figure Captions

Figure 1. System 1C performance statistics 12/3/08-12/2/09
Figure 2. System 1D performance statistics 12/3/08-12/2/09
Figure 3 Integrated SOFC and Hydrogen Pump Fluid Schematic
Figure 4 Estimated H2 Production
Figure 5 Baseline SOFC performance over approx 1 month without H2 pumping
Figure 6 10-day average SOFC performance with H2 pump in recycle mode
Figure 7. Hydrogen cost analysis using the DoE H2A Model
Figure 8. Hydrogen cost analysis adding the Value of Electricity