VI.E.2 Validation of an Integrated Hydrogen Energy Station

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FuelCell Energy, Danbury, CT

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Objectives

Demonstrate the technical and economic viability of a hydrogen energy station using a high-temperature fuel cell designed to produce power and hydrogen from natural gas.

- Complete a technical assessment and economic analysis on the use of high-temperature fuel cells (HTFCs), including solid oxide fuel cells (SOFCs) and molten carbonate fuel cells (MCFCs), for the co-production of power and hydrogen from natural gas (energy park).
- Build on the experience gained at the Las Vegas H2 Energy Station and compare/contrast the two approaches for co-production.
- Determine the applicability of HTFC co-production for the existing merchant hydrogen market and for the emerging hydrogen economy.
- Demonstrate the concept at a suitable site with demand for both hydrogen and electricity.
- Maintain safety as the top priority in the system design and operation.
- Obtain adequate operational data to provide the basis for future commercial activities, including hydrogen fueling stations.

Technical Barriers

This project addresses the following technical barriers from the Technology Validation section (3.5.4.2) of the Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan:

(B) Storage
(C) Hydrogen Refueling Infrastructure
(I) Hydrogen and Electricity Coproduction

Technical Targets

This project will contribute to achievement of the following DOE technology validation milestones from the Technology Validation section of the Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan:

Milestone 16: Demonstrate prototype energy station for 6 months; projected durability >40,000 hours; electrical energy efficiency >40%; availability >0.80. We will be demonstrating the use of a molten carbonate fuel cell (FuelCell Energy's DFC-300) to produce power and electricity for a minimum of 6 months. Current process projections put the electrical efficiency at 49%. Based on actual field performance data, both the durability and availability of the technologies selected for demonstration are expected to exceed the milestone values.

Milestone 17: Validate prototype energy station for 12 months; projected durability >40,000 hours; electrical energy efficiency >40%; availability >0.85. See explanation under Milestone 16 above.

Accomplishments

- Completed the preliminary design and engineering development efforts with FuelCell Energy to recover hydrogen from an FCE DFC-300 MCFC. In addition, component testing of critical unit operations was completed. A bottom-up cost estimate was completed for the system, and economics were validated.
- Details on the accomplishments for the anode off-gas removal system, hydrogen purification system and overall integration follow:
  - *Anode off-gas removal*: Completed a preliminary process design to increase the hydrogen content in the anode off-gas and recover high-grade heat from the anode off-gas. Component testing was completed for a range

of water-gas-shift catalysts, heat exchangers, condensing systems, and anode gas filters.

- Evaluated design options for processing anode exhaust
- Assessed safety and control requirements for integrating direct fuel cell power plants with H_2 separation subsystem
- Developed preliminary piping and instrumentation diagram
- Sized processing equipment
- Completed cost estimates
- Developed preliminary layout
- Tested critical components

– *Hydrogen purification*: Completed the selection and preliminary design of a pressure swing adsorption (PSA) process for hydrogen recovery and purification.
  - Cycle simulation completed
  - Adsorbent mix selected
  - Lab testing completed
  - Pilot plant verification completed
  - PSA design optimized for high recovery with minimal electrical work
  - Cost estimate completed
  - Patent applications in progress

– *System integration*: Completed the integration design, revised the capital and operating cost estimates and recalculated the cost of hydrogen using a financial model. The following items were completed:
  - Process Flow Diagram
  - Heat and Material Balance
  - Plot Plan
  - Technical Risk Plan
  - Preliminary HAZOP
  - Process Control Strategy
  - Start-up/Shutdown Plan
  - Installation/Construction
  - Testing Strategy
  - Security Review

Introduction

One of the immediate challenges in the development of hydrogen as a transportation fuel is finding the optimal means to roll out a hydrogen-fueling infrastructure concurrent with the deployment of hydrogen vehicles. To meet this challenge, distributed generation of hydrogen has been proposed as a potential sourcing solution. However, the low-volume hydrogen requirements in the early years of fuel cell vehicle deployment and the sporadic nature of vehicle fueling make the economic viability of stand-alone, distributed hydrogen generators particularly challenging. One significant challenge for fueling station developers will be minimizing the financial risk associated with stranded capital assets. A potential solution to this "stranded asset" problem is the use of hydrogen energy stations that produce electricity in addition to hydrogen. One such station concept that shows promise, as concluded in Phases 1 and 2 of this project, is the use of high-temperature fuel cells to co-produce hydrogen and electricity. It was concluded in Phases 1 and 2 that high-temperature fuel cells configured to co-produce hydrogen and electricity have the potential to meet the DOE hydrogen cost targets, while producing power for less than $0.10/kW. To validate this conclusion, a four-phase project is being undertaken to design, fabricate and demonstrate the co-production concept from a HTFC. The basis of the demonstration will be a FuelCell Energy DFC-300 Molten Carbonate Fuel Cell modified to allow for the separation and purification of hydrogen from the fuel cell anode exhaust using an Air Products-designed hydrogen purification system.

A simple process flow diagram of the hydrogen co-production concept based on the FuelCell Energy DFC-300 is shown in Figure 1. The high-efficiency direct fuel cell (DFC) works on the following thermodynamic principles:

1. Internal reforming of natural gas to produce H_2:
   $CH_4 + 2H_2O \rightarrow CO_2 + 4H_2$ (Endothermic)
2. Anode reaction:
   $H2 + CO_3^{=} \rightarrow H_2O + CO_2 + 2e\text{-}$
3. Cathode reaction:
   $CO_2 + \frac{1}{2}O_2 + 2e\text{-} \rightarrow CO_3^{=}$ (Exothermic)

The DFC technology is based on internal reforming of fuels inside the fuel cell, integrating the synergistic benefits of the endothermic reforming reaction with the

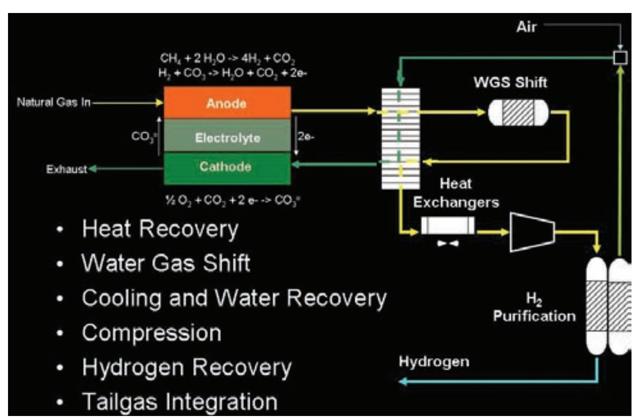

FIGURE 1. Process Flow Diagram

exothermic fuel cell reaction. The internal reforming of methane is driven by the heat generated in the fuel cell and simultaneously provides efficient cooling of the stack, which is needed for continuous operation. The steam produced in the anode reaction helps to drive the reforming reaction forward. The hydrogen produced in the reforming reaction is used directly in the anode reaction, which further enhances the reforming reaction. Overall, the synergistic reformer-fuel cell integration leads to high (~50%) electrical efficiency.

The baseline electric DFC is designed to operate at 75% fuel utilization in the stack. The remaining 25% of fuel from the anode presents a unique opportunity for low-cost hydrogen, if it can be recovered from its dilute form. The recovery and purification of hydrogen from the anode presents several challenges:

1) The anode off-gas is a low-pressure, high-temperature gas stream that contains <15% hydrogen by volume.
2) The anode exhaust stream must be heat integrated with the fuel cell to ensure high overall system efficiency.
3) The parasitic power used for purification must be optimized with the hydrogen recovery and capital cost to enable an economically viable solution.

Over the past year Air Products and FuelCell Energy completed complementary parallel engineering development and design programs to address the above challenges. The required equipment and unit operations for hydrogen recovery from the anode of a DFC fuel cell can be seen in Figure 1.

Approach

A hydrogen energy station that uses a high-temperature fuel cell to co-produce electricity and hydrogen will be evaluated and demonstrated in a four-phase project, with a go/no-go decision after Phases 2 and 3.

In Phase 1, Air Products completed a feasibility study on the technical and economic potential of HTFCs for distributed hydrogen and power generation. The applicability of this concept to the existing merchant hydrogen market and the hydrogen economy was explored. As part of the Phase 1 analysis, three different high-temperature fuel cells were evaluated to determine the technology most suitable for a near-term demonstration. FuelCell Energy's DFC-300 technology was selected for concept development.

In Phase 2, a process design and more thorough bottom-up cost estimate was completed for the hydrogen energy station that integrates FuelCell Energy's DFC power plant (Model DFC300 series) with a PSA system selected and designed by Air Products. All costs for major equipment were based on actual equipment, fabrication, and installation quotes. The overall economics of the co-production system were updated to reflect the new capital and operating cost estimates. Technical risks were identified. The high-level risks are being managed and addressed by critical component testing, laboratory testing, and pilot plant operation.

In Phase 3, a detailed design for the co-production system will be completed. The system will be fabricated, shop tested, and installed in the field. Prior to shipping to the field, the entire co-production system will be installed and operated at FuelCell Energy's facility in Danbury, CT., which will allow for more convenient and efficient system check-out.

In Phase 4, the system will be moved from FCE's facility to a suitable demonstration site. Once in the field, the co-production system will be operated for a minimum of six months. During this period, performance tests will be conducted to validate the DOE targets and the economics of the system.

Results

Updated performance projections based on the design and component testing completed in Phase 2 can be seen in Table 1. The overall system performance exceeds the preliminary estimates made in Phase 1 and supports the economic viability of the co-production system. Furthermore, the results of the process and component testing completed as part of Phase 2 verify the technical viability and support the performance requirements necessary to make the co-production system an economically attractive route for distributed hydrogen production.

Significant improvement in PSA performance was achieved as a result of the engineering development work undertaken over the past year. Preliminary estimates from Phase 1 indicated the hydrogen recovery from the PSA would be 75% with a 300 psig inlet

TABLE 1. Overall Performance Projections

	Units	Phase I	Phase II
Overall Efficiency (Net Power + Hydrogen Product) / (Fuel)	LHV	60%	66%
Power Efficiency Net Power / (Total Fuel – Hydrogen Product)	LHV	49%	49%
Hydrogen Efficiency (Hydrogen Product – Purification Power) / Hydrogen Product	LHV	68%	77%
Hydrogen Product	Nm3/hr	~ 40	~ 80
Net Power w/o & w Hydrogen	kW	~ 247 / 207	~ 300 / 243
Natural Gas Flow	Nm3/hr	~ 55	~ 74

pressure. Through innovative cycle design work and the selection of the optimal adsorbents completed over the past year, PSA recovery was improved to over 85% with a 150 psig inlet pressure. Achieving a higher recovery with less compression power significantly improves the economics of the co-production system. The improved PSA performance was verified with pilot plant runs. A patent application is in progress that covers the advances made in the cycle design that enable a high recovery of hydrogen in this application with low parasitic power.

A plot plan was developed using the preliminary process design and equipment specifications. A 3-D rendering of the proposed co-production system can be seen in Figure 2. The footprint is approximately 50 ft x 50 ft. The entire system consists of skidded modules for ease of transportation and installation.

Detailed bottom-up cost estimates were completed for co-production systems using both the FuelCell Energy DFC-300 and DFC-1500 product lines. Costs for the major pieces of equipment and costs for fabrication are based on actual vendor quotes. Installation estimates were developed by the Air Products Construction group. To match the fueling station criteria in the Multi-Year Program Plan, two DFC-1500s would be required. In this configuration a total of 1,400 kg/day of hydrogen would be produced with a net power production from the fuel cell of 2.4 MW. Using H2A criteria with the Solid State Energy Conversion Alliance (SECA) capital cost targets for the fuel cell resulted in a hydrogen price of $1.63/kg. In this scenario power is being sold for 8 cents/kWh. It is important to note that the hydrogen price does not include the fueling station equipment.

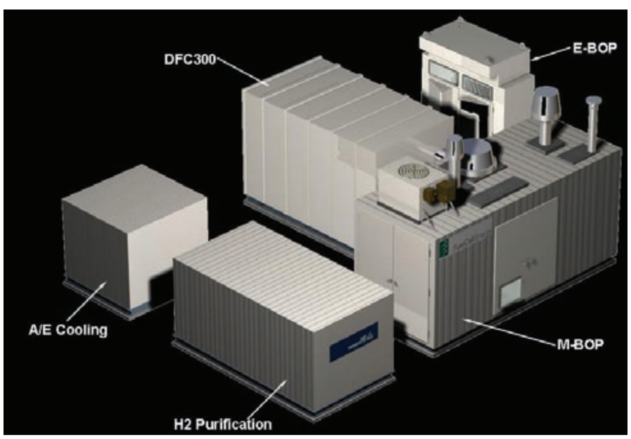

FIGURE 2. Energy Station Rendition

Conclusions and Future Directions

The work completed over the past year continues to validate that HTFCs configured to co-produce hydrogen and electricity can result in significantly lower costs for distributed hydrogen production, while generating power at commercially attractive rates.

- HTFCs configured to co-produce hydrogen and electricity have the ability to meet the DOE hydrogen cost targets as specified in the Multi-Year Program Plan, while producing power for less than $0.10/kW.
- The FuelCell Energy DFC-300 is the preferred fuel cell system to demonstrate the potential of co-production using high-temperature fuel cell technology.
- Based on the preliminary process design and initial process/component testing, the hydrogen energy station proposed in this project will meet or exceed the DOE validation milestones and continue to support the economics completed in Phase 1.
- The anode exhaust from a DFC-300 can be cost effectively and efficiently recovered using an adsorption-based purification system.

Future Direction

- Complete the detailed design, construction, and installation of the energy station (Phase 3).
- Select a site for the demonstration.
- Operate, performance test, and collect data on the energy station for a minimum of six months (Phase 4).

FY 2006 Publications/Presentations

1. Keenan, G. R., and Pinakin Patel, "Hydrogen Co-production from a Molten Carbonate Fuel Cell," 2005 Fuel Cell Seminar, November 2005, Palm Springs, CA.