V.K.2 Development and Demonstration of a New-Generation High Efficiency 10 kW Stationary Fuel Cell System

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Fiscal Year (FY) 2011 Objectives

- To identify core technology improvements, methodologies and engineered solutions to overcome challenges facing the development of fuel cells (FCs) for use in combined heat and power (CHP) applications.
- To design an integrated system based on the most promising down-selected fuel cell and fuel processor building blocks.
- To build and test a prototype unit in a laboratory setting and collect 300 hours of operating data.
- To optimize, redesign and retrofit a pressure swing adsorption (PSA) unit using lessons learned from prototype to develop a field demonstrator.
- Conduct a six month demonstration in an International Partnership for the Hydrogen Economy country.

Technical Barriers

This project addresses the following technical barriers from the Fuel Cells section of the Fuel Cell Technologies Program Multi-Year Research, Development and Demonstration Plan:

(A) Durability
(B) Cost
(C) Performance

Technical Targets

Work under the project is aimed at developing novel fuel processing, polymer electrolyte membrane (PEM) fuel cell technologies and integration strategies in order to make progress toward achieving DOE targets for stationary PEM fuel cell power systems for year 2011. These targets and project progress are shown in Table 1.

TABLE 1. DOE Targets vs. Project Achievements

Metric	2010 Project Status	2011 Project Achievement	2011 DOE Target[1]
Electrical efficiency at rated power	32.6%-prototype	To be determined-demonstration unit testing underway	40%
CHP energy efficiency	60.8%-prototype	To be determined -demonstration unit testing underway	80%
Operating lifetime	832 hours on hydrogen generator	3,425 hours on hydrogen generator[2]	40,000 hours

[1]Complete DOE Table 3.4.4 found at http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/pdfs/fuel_cells.pdf
[2]Accumulated on prototype, new retrofit hydrogen generator integrated into demonstration CHP unit now under test through February 2012.

Other challenges being addressed under the project are:

- Reduced startup time by improved thermal management design.
- Reduced size by improved subassembly integration and packaging.

FY 2011 Accomplishments

- Conformité Européenne ("European Conformity") compliant design of demonstration unit resulting in:
  - 30% size reduction.
  - Grid tie enabled using commercial solar photovoltaic inverter.
  - Integrated feed gas compressor, water system and gas quality monitoring.
  - On-board safety and emissions management.
  - System health monitor with remote data acquisition and analysis for predictive maintenance.
  - Twin stack fuel cell system developed for CHP application to improve system efficiency.
  - Modeled combined heat and power efficiency increased to 78%.[1]

[1] Expected performance based on model of updated system developed during retrofit redesign and new optimization approach: actual validation testing planned for Q4 FY 2011 - Q2 FY 2012 thus is noted as to be determined in Table 1.

- Modeled natural gas-to-electrical efficiency of 37%.[2]

- Construction of field demonstration unit.
- Prove-out of the feasibility of adsorption enhanced reforming (AER) as a potential lower cost fuel processor option (eliminates expensive alloys and PSA required by steam methane reformer [SMR] technology).

Table 2 shows run-time hours of the prototype between those reported last year versus additional time logged since then (for FY 2011). The mode of particular importance is that for pure hydrogen production; the increase in hours logged by more than 70% without loss of mechanical integrity and/or notable deterioration in fuel conversion is indicative of a fundamentally sound reformer design.

TABLE 2. Accumulated Hours on Prototype

Mode	Hours-FY 2010	Hours-FY 2011
Hot-Idle[1]	2,164	3,425
Pure Hydrogen Production	832	1432
Power Production	396	733

[1] Reformer combustor hot (700°C) only without synthesis gas or power production occurring.

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Introduction

The development of highly efficient and cost-effective clean energy solutions is not without challenge. Hydrogen fuel cell technologies are expected to become a significant player in reducing our dependence on imported fossil fuels and curb the further accumulation of greenhouse gases and criteria pollutants.

This project is focused on the design, fabrication and field demonstration of a stationary CHP system that will provide multi-dwelling residential and light commercial end-users with on-site generated electrical and heating needs. The proposed technology addresses DOE targets by using PEM fuel cell stacks as they have been proven to achieve high efficiency, greater durability and lower costs than competing fuel cell technologies.

Approach

The approach to achieving this project's 40% electrical efficiency target is incremental and based on (1) optimization of the SMR+FC architecture and (2) the development of an 80% or greater thermally efficient AER hydrogen generator that can "plug-and-play" into the same SMR+FC hydrogen feed interface. The SMR+FC optimization relies on allowing slightly less than 100% hydrogen to enter the FC (99% H_2, balance methane [inert to the FC]) which has a negligible impact on the FC performance, but allows for increased hydrogen recovery from the processor whereby its thermal efficiency can be boosted from 70% up to as much as 73%. Process simulations indicate that this method when combined with the benefits of a twin-stack FC configuration can increase the overall CHP system electrical efficiency from its current status of 32.6% (achieved on prototype last year) to approximately 37% (demonstration unit now under test).

An AER hydrogen generator produces a feed stream similar to what the optimized SMR+FC system would receive but operates at 500°C versus 900°C. This means less external energy is needed for AER making it more thermally efficient than SMR. Predictive models developed for us by Sandia National Laboratories during Year 1 of the project indicate that an efficiency of up to 85% can be achieved with the AER compared to only 70%-73% which is the maximum one can obtain with SMR. The product of the AER hydrogen generator and the fuel cell efficiencies, less 12% (assumed value) for the parasitic power requirements to run the CHP system ([0.85 x 0.55] -0.12), would result in a total system electrical efficiency of approximately 41%. Furthermore, with AER, carbon dioxide removal and reforming occur simultaneously thereby eliminating the need to have an additional purification step (such as a PSA) ultimately leading to lower cost and smaller system. Our work on AER culminated in Year 2 as further development and funding is required to mature the technology to the point of a "plug-and-play" swap of SMR.

At the beginning of this last year of the project, a twin-stack FC configuration was chosen for integration into the CHP demonstrator. Since each of the two stacks can run at a lower output and be combined to produce 10 kW, the efficiency of each stack will be at its maximum point thereby synergistically operating together to achieve an improvement of efficiency from 53% (single stack) to 59%. The result of using two stacks together in terms of total performance can be seen in Figure 1 of the Results section.

Results

Over the course of FY 2011, our project team focused on (1) twin-stack fuel cell system development and testing, (2) stack testing to evaluate the effect on efficiency when feeding 99% hydrogen (balance methane) vs. 100% hydrogen, and (3) a retrofit design and repackaging to accommodate a shorter PSA for the purpose of optimization through relaxing the hydrogen purity requirement all while achieving a system size reduction.

As was determined experimentally (Figure 1) at the 10 kW nominal load to which the CHP system has been designed, a twin-stack configuration performs notably better than a single stack when considered as a total system. The efficiency of a single stack reaches its maximum at approximately 5 kW, while having twin stacks it is possible to run each at this mid-range load and achieve a combined efficiency of 59% vs. 53%.

[2] See footnote 1: prototype achieved 32.6% electrical efficiency-increase to 37% predicted by model of updated system.

According to our latest model that forms the design basis of the retrofitted demonstrator, this approach alone adds 1%-2% to the overall CHP system electrical efficiency. Thermal management of the reformer and the reduction of parasitic power demands from the balance of plant also contribute to improving efficiency over the prototype developed in FY 2009-10.

In conclusion, using a twin-stack configuration can increase system efficiency up to 59%:

- The higher voltage output of two stacks enables grid-tie via a commercially available photovoltaic inverters without a boost converter.
- May extend life and ultimately decrease costs as each stack operates at a lower nominal load.
- Air blower output is shared across stacks thus reducing its back pressure and parasitic power draw.

To better understand the potential impact on efficiency running our PEM stacks with less than 100% pure hydrogen in support of our SMR+FC optimization approach, our Research and Technology Group made rig modifications required to run mixes of hydrogen (99%) and methane (1%). Tests were run on a 20-cell evaporatively cooled stack with hydrogen to air stoichiometry of 2:1.

Stack testing was performed over 15 hours during which period our team determined that the mean cell voltage was not adversely impacted by using the mix. Figure 2 depicts a baseline and overlay of cell voltages for pure hydrogen and the mix, respectively.

The work also confirmed that operating the FC with the mix requires more frequent anode purging than when using pure hydrogen in order to maintain the same cell voltage: at 100 A the purge frequency would need to be increased to 5 seconds compared to 6.4 seconds. It should be noted that this hydrogen does not necessarily have to be lost because when the FC is integrated into a CHP unit, the stream is blended into the same fuel that goes to the reformer. As the demonstration unit now under test has been designed to Conformité Européenne directives whereby it must comply with strict combustible emissions limits, it does indeed recycle this hydrogen.

In parallel to developing the twin-stack fuel cell system and conducting bench tests with 99% hydrogen, our mechanical and process design teams spent a great part

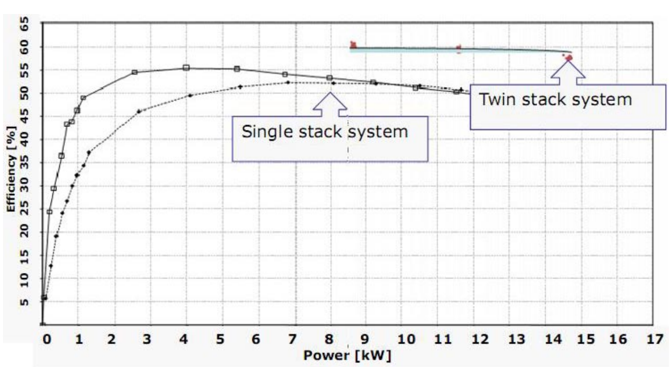

FIGURE 1. Twin-Stack System Efficiency vs. Single Stack Configuration

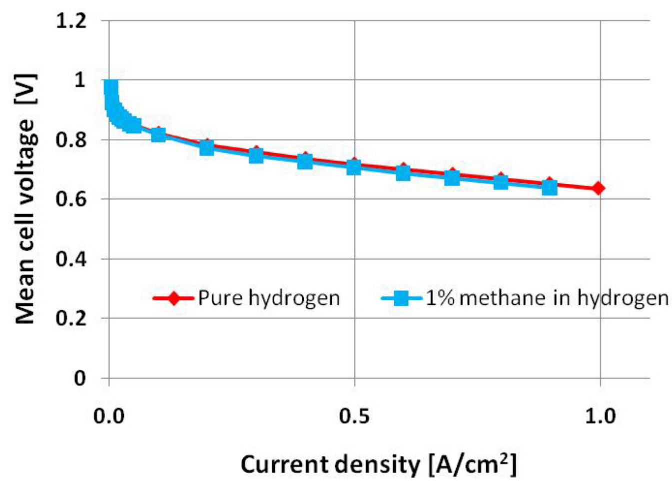

FIGURE 2. Mean Cell Voltage with 99% H_2 Feed vs. 100% H_2 Feed

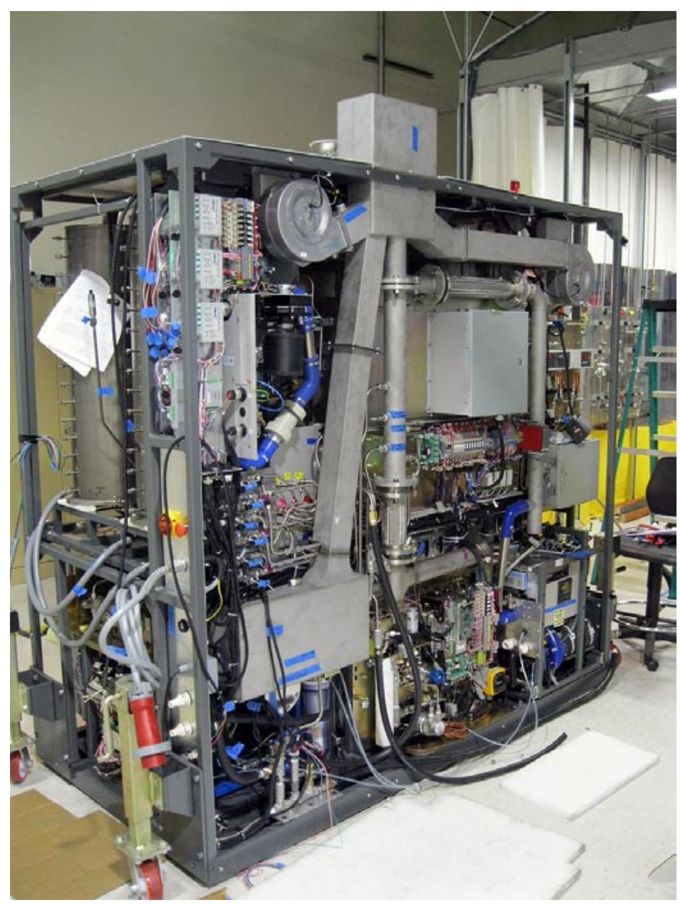

FIGURE 3. Retrofit Demonstration Unit

FIGURE 4. Packaged Demonstration Unit

of this last year evolving the CHP system "from project to product." The demonstration unit shown in Figure 3 and Figure 4, was subjected to IE's normal four stage-gated design review process which facilitated being able to reduce the number of subsystems from 23 (on prototype) down to just nine. Key component suppliers were also engaged early on to provide a purpose built PSA that is 1.5' shorter than the previous generation, and a natural gas compressor suitable for integration within the main frame by being less than one third in size compared to its equivalent standard model.

The field unit of course must meet all safety and environmental regulations as mandated by the European Union, and as such has been implemented with an emissions monitoring and redundant, hard-wired safety shut down subsystem that constantly watches over the main system controller and software. The unit was also designed for ease of installation requiring that the site connections comprise nothing more than city water and gas, drain, heating water inlet and outlet, network connection, and flue. Components that will demand periodic maintenance while under field trial are located in areas of the machine that provide quick and easy access (e.g. water filters, sulfur adsorbent, etc.).

FIGURE 5. Greenwatt Way Demonstration Site

While on site, the system will show real-time status and performance data on a local user interface while also being streamed back to IE headquarters. Startup and shutdowns will normally occur based on those commands the unit receives from the site's own energy management system.

In addition to designing and building the demonstration unit this last year, the planned site received National Environmental Protection Act (NEPA) determination as required by the project and federal law. A six-month field trial will take place 40 miles southwest of London, England at a multi-residential housing development called Greenwatt Way. This site is owned by Scottish and Southern Energy with whom IE has formed a joint venture and will serve to showcase green technologies and provide housing for up to eight families. A conceptual layout of the site can be seen in Figure 5.

Conclusions and Future Directions

- 2010 - Demonstration site receives NEPA determination.
- 2011 - Conformité Européenne compliant field demonstrator designed and built:
  - Approximately 30% smaller than prototype.
  - Projected system electrical efficiency increased to 37%.
  - Added functionality.
- 2011 - Testing of fuel cell stacks with 99% hydrogen showing no adverse impact:
  - Allows for the evaluation of system level trade-off between FCS and H_2 generator to maximize performance.
- 2012 – Six-month field demonstration and project closure:
  - Logan Energy to provide installation and system maintenance support.
  - System health monitor will relay real-time data back to the IE Knowledge Center.
  - Energy store will showcase ground-source heat pump, biomass boiler, photovoltaic and CHP system.

Patent Pending

1. K. Duraiswamy, A. Chellappa; Hydrogen Generation Utilizing Integrated CO_2 Removal With Steam Reforming, WO/2011/075490.

FY 2011 Publications/Presentations

1. K. Duraiswamy, A. Chellappa, G. Smith, Y. Liu, M. Li. "Development of High Efficiency Hydrogen Generators for Fuel Cell based Distributed Power Generation", Intl. J. Hydrogen Energy, 35(17), 2010, p 8962-8969.

2. M. Li and K. Duraiswamy. Process integration of adsorption enhanced reforming for use in conjunction with fuel cell. In The 21st International Symposium on Chemical Reaction Engineering, Philadelphia, PA, 2010.

3. Mingheng Li and Kandaswamy DuraiSwamy, Development of a High-Efficiency Hydrogen Generator Based On Adsorption Enhanced Pulsing Feed Reforming, presented at the AIChE Annual meeting, Salt Lake City, Nov 2010.

4. K. Durai Swamy, Diane Aagesen, Chris Jackson "Development and Demonstration of a New Generation High Efficiency 10kW Stationary PEM Fuel Cell System", U.S. DOE Annual Merit Review Proceedings, Arlington, VA. May 9, 2011.