2011 DOE Hydrogen Program Annual Merit Review

Development and Demonstration of a New Generation High Efficiency 10kW Stationary PEM Fuel Cell System

May 9-13, 2011

PI: Kandaswamy Duraiswamy PhD, PE

Diane Aagesen

Chris Jackson PhD, CEng

INTELLIGENT ENERGY

Clean fuel and power

FC 031

This presentation does not contain any propriety, confidential or otherwise restricted information

Overview

Timeline

Start Date: July 2007

End Date: August 2011

Percent Complete: 82%

Budget

Total : $4,998,938

Total DOE obligation: $2,404,863

Funding received through 12/2010: $2,350,562

Funding remaining in FY11= $54,301

Project Partners

- California Polytechnic University, Pomona
  - Materials development, modeling and adsorption enhanced reforming (AER) bench testing
- Univ. of South Carolina
  - AER modeling
- Sandia National Labs
  - Systems modeling
- Intelligent Energy Ltd.
  - Development and supply of fuel cell system
- Scottish Southern Energy
  - Demonstration site

Barriers	DOE 2012 Target
Electrical Efficiency	40%
Overall Efficiency	85%
Durability	30,000 hrs
Capital Cost	$650/kW
Start-up Time	45 minutes

Relevance

- **Project: To Develop a High Efficiency 10kW PEM Fuel Cell CHP System and Demonstrate in IPHE Country (UK)**
- **Project Objectives for 2011 to Progress Towards DOE Targets**

DOE 2011 Target	Project Objectives	2011 Objectives
40% electrical efficiency	**40% electrical efficiency**	**Study impact of operating stacks on 99% hydrogen as approach to improve system level efficiency***
80% overall efficiency	**>70% efficiency**	**Build and test an integrated system with multiple heat recovery streams**
40,000 hours durability	**40,000 hours durability**	**Real-world conditions field demonstration with system health monitoring**

- **Cost-saving approach**

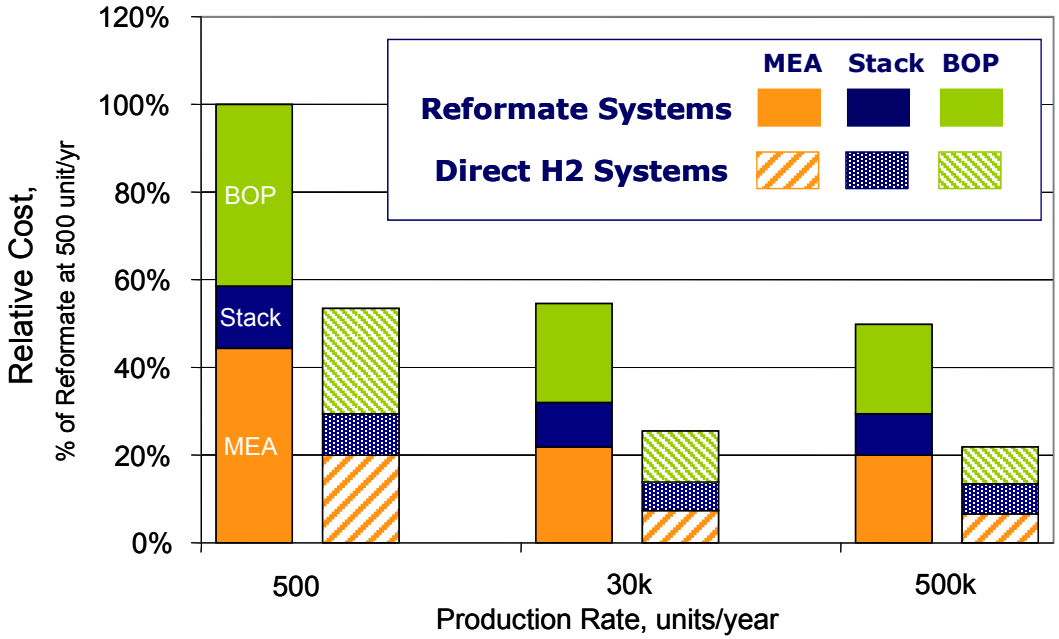
  Pure hydrogen, high efficiency PEM FCs suitable for **multiple applications**
  Implementing a core systems engineering and subsystems integration approach
  Volume cost reduction strategy "design once, deploy many times"

*Mimics alternative fuel processor (AER) feed stream

Approach

Phased Development of an Open Architecture System with a Pure H_2* Interface Between the Fuel Cell & Fuel Processor

- Advantages
  - Improved fuel cell performance
  - Increased fuel cell lifetime
  - Lower fuel cell cost
  - Smaller reformer
  - High fuel utilization
  - Simplified integration
  - Independent operation of fuel cell, fuel processor
  - "Plug and Play"



– **Task 1**-Technology Building Blocks Development and Evaluation (100% Complete)

– **MILESTONE: GO/NO-GO #1 DECISION ACHIEVED** ✓

– **Task 2**-CHP Prototype Engineering Design and Configuration (100% complete)

– **Task 3**-CHP Prototype Construction and Validation Testing (100% complete)

MILESTONE: GO/NO-GO #2 DECISION ACHIEVED ✓

– **Task 4**-CHP system retrofit, optimization and field demonstration (50% complete)

*99% or greater

Approach

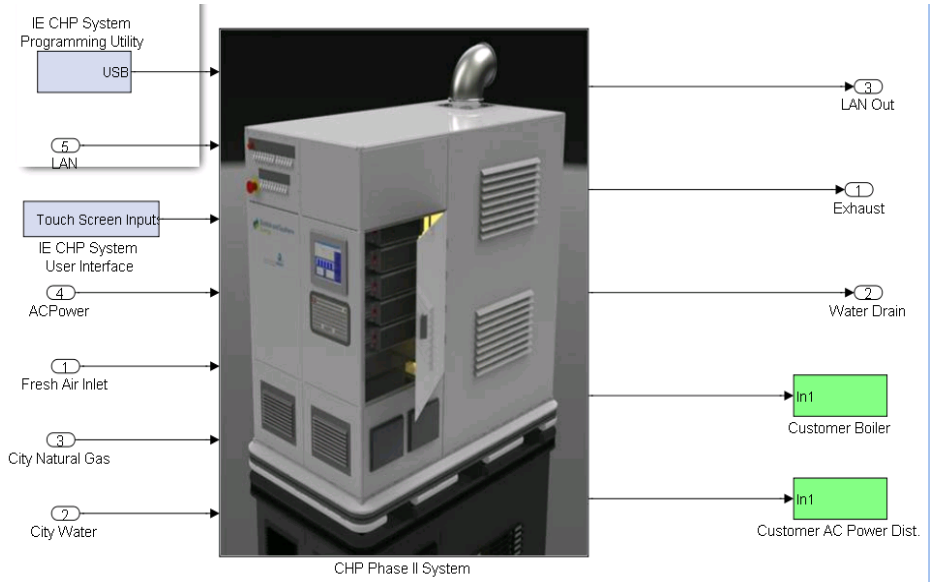
Phased Development of an Open Architecture System with a Pure H_2* Interface Between the Fuel Cell & Fuel Processor

- **Task 1**-Technology Building Blocks Development and Evaluation
  - Down selection to evaporatively cooled (EC) fuel cell stack and steam methane reforming (SMR) fuel processor due to most promising combined efficiency for near-term demonstration
  - Membrane reformer and air-cooled stacks ruled out due to lower efficiencies and inappropriateness for market segment (scale) being addressed in our nearest-term commercialization plans
- **Task 2**-CHP Prototype Engineering Design and Configuration
- **Task 3**-CHP Prototype Construction and Validation Testing
  - Integration of best-option building blocks to validate system performance and assess appropriateness for field demonstration
- **Task 4**-CHP system retrofit, optimization and field demonstration
  - Go-decision reached based on an opportunity to increase system efficiency through unique approach toward subsystems trade offs—using 99% hydrogen vs. 100%
  - Develop CE compliant field unit to advance system architecture/flexibility and verify through real-world trials via remote monitoring of performance
- **Parallel development of AER technology to progress toward greater than 40% electrical efficiency**

***99%**

Approach

- Model-based systems engineering using industry standard software
  - **Address trade-offs for optimization at both subsystem and system level**
- End-to-end system integration with prototype test and validation unit (SMR + PSA 2010/11)
  - **Real data for model inputs**
  - **Automated controls development**
  - **Multiple level safety systems**
- CE certification (SMR + PSA *4/2011)* →
  - **Addresses safety and manufacturability**
- Pure hydrogen PEM FC
  - **Addresses durability**
  - **Addresses high electrical efficiency**
  - **Addresses lower costs**



Inside the Customer's Facility

- Low cost, highest efficiency hydrogen generator will plug into existing architecture (*AER 2012/13- Proposal submitted for funds-FOA-0000360*)

CHP Technical Accomplishments Prototype[A] -Previous Work [Tasks 2/3]

System Component	Operating Hours
Combustor	3425
Reforming	1626
PSA	1432
FC	730

Continued operation of the prototype to support field demonstration unit[B] development

- Successful automation from cold to hot idle and hot idle to full H_2 generation
- The prototype controls and procedure were modified to test warm start capabilities intended for the field demonstration unit. This helps smooth out transitions to and from hot idle, and through warm start
- The controls team added error code notifications for shut downs to the Prototype system. These notifications will be used on the demonstration unit

[A] Prototype is defined as laboratory test rig only (Task 2/3)

[B] Demonstration unit is defined as CE marked, field deployed (UK) system (Task 4)

CHP Technical Accomplishments Prototype-Previous Work [Task 2/3]

	Expected Initial Performance @ 10kW	Achieved with Prototype @ 11kW (Task 2/3)	Projected Performance of Demonstrator (Task 4)
Pure Hydrogen Produced (SLPM)		135	
Natural Gas Fed to Reformer (SLPM)		54	
Natural Gas Fed to Combustor (SLPM)		6.3	
Hydrogen fed to Combustor (Proxy for PSA off-gas) (SLPM)		5	
Fraction of Natural Gas Power Converted to Pure Hydrogen	72%	68.2%	73%
Fuel cell Gross power (W)		11540	
Hydrogen Consumed by Fuel Cell (SLPM)		120	
Gross Efficiency of Fuel Cell	53%	53.4% ✓	59%
Fuel cell parasitic power (W)	720	620 ✓	620
Hydrogen production parasitic power (W)	850	610 ✓	610
Percentage of DC Power Available to Customer		89.4%	86.1%
End-to-End Electrical Efficiency (Electricity Out / LHV Fuels In)*	33.2%	32.6%	37.1%
Thermal Power Recovered from Hydrogen Generator (W)	4200	2732	3500
Thermal Power Recovered from Fuel Cell (W)	4200	6640 ✓	9000
End-to-End Thermal Efficiency		30.1%	41.1%
Overall Combined Heat and Power Efficiency	61.1%	60.8%	78.2%

Prototype unit achieved four of eight initially expected internal performance metrics

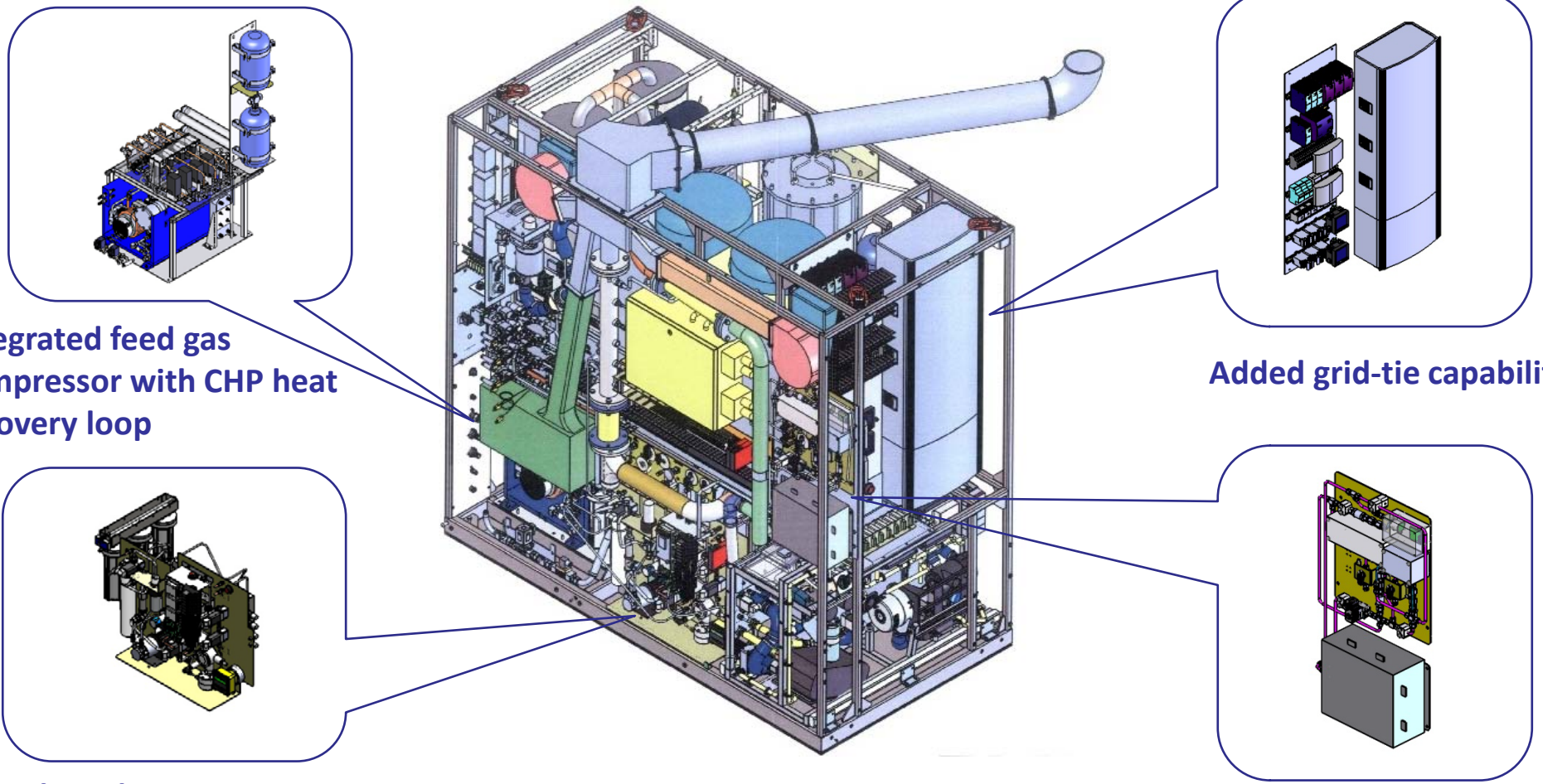
*NG compression and DC/AC inversion demands not factored in

CHP Technical Accomplishments Demonstration Unit [Task 4]

- CE compliant detailed engineering of demonstration unit (with PSA retrofit) resulting in:
  - 30% size reduction
  - Grid tie enabled using commercial solar PV inverter
  - Integrated feed gas compressor, water system and gas monitoring capability
  - System Health Monitor with remote data acquisition and analysis for predictive maintenance
  - Twin stack developed to improve system efficiency, lower long-term costs and benefit from economies of scale
  - Combined heat and power efficiency increased to 78%
  - End-to-end electrical efficiency increased to 37%
- Construction of field demonstration unit
- PSA alternative technology options for cost reduction strategies identified through feasibility tests (AER)

CHP Technical Accomplishments
Demonstration Unit [Task 4]

Retrofit engineering and build



Integrated feed gas compressor with CHP heat recovery loop

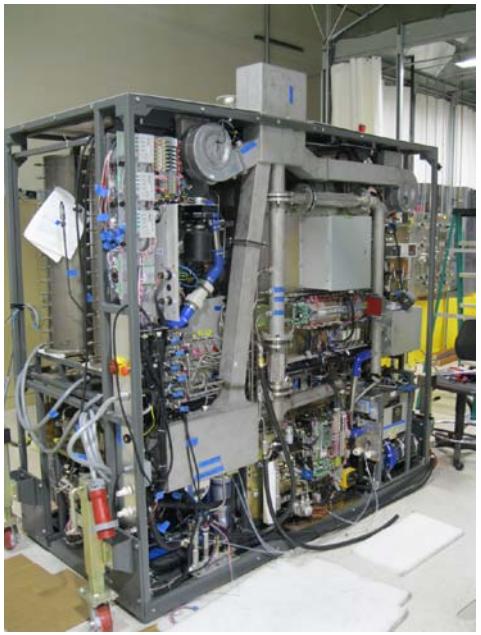
Added grid-tie capability

On-board water management

Integrated diagnostic capability

CHP Technical Accomplishments Demonstration Unit [Task 4]

Retrofit engineering and build

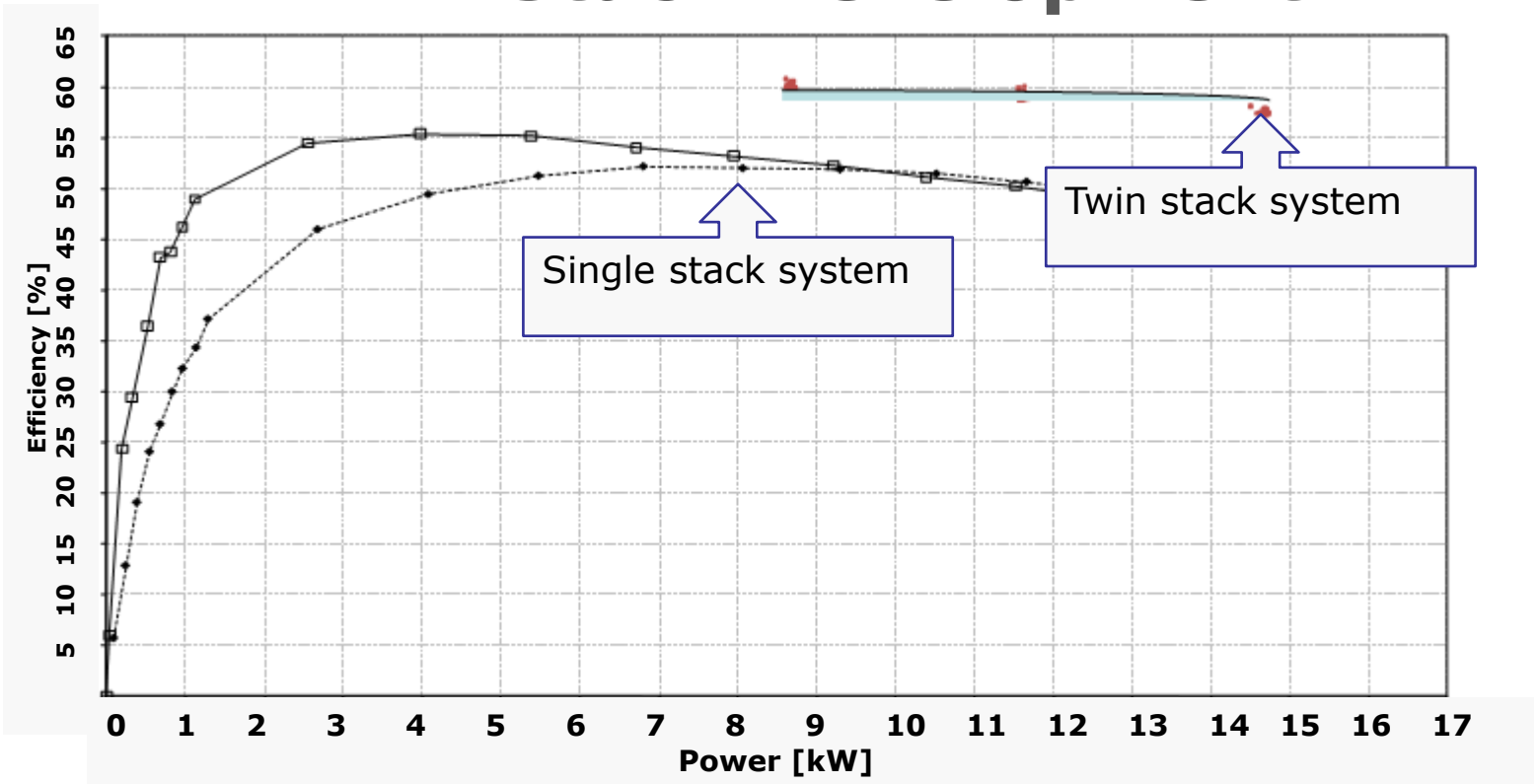


- **Prototype test rig**
- **8’ x 4’ x 10’ without:**
  - Integrated fuel delivery
  - Integrated water management
  - Integrated gas analysis
  - Grid-tie inverter functionality

- **Fully integrated demonstration unit and:**
  - ~30% smaller

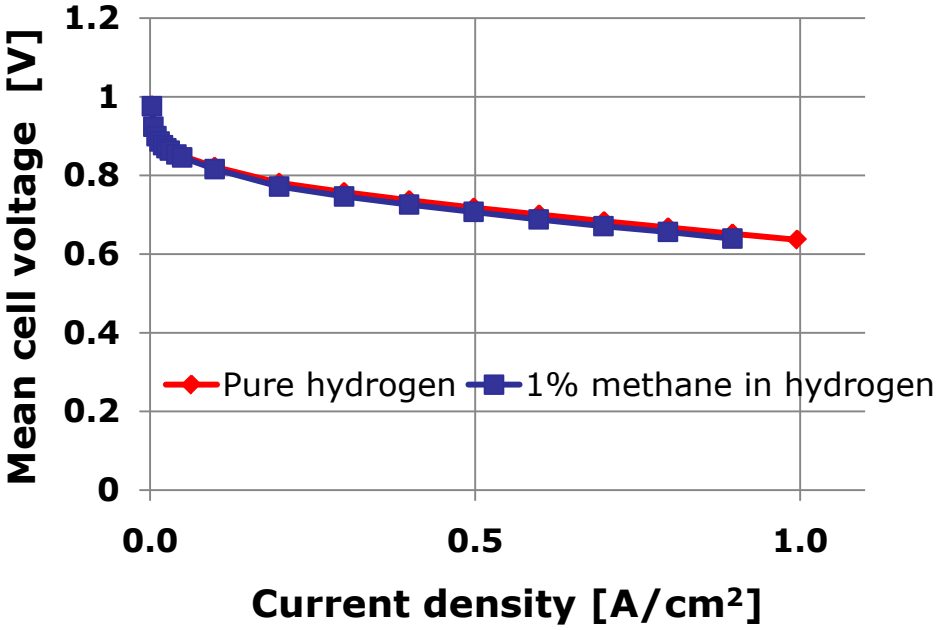
- **Packaged demonstration unit**

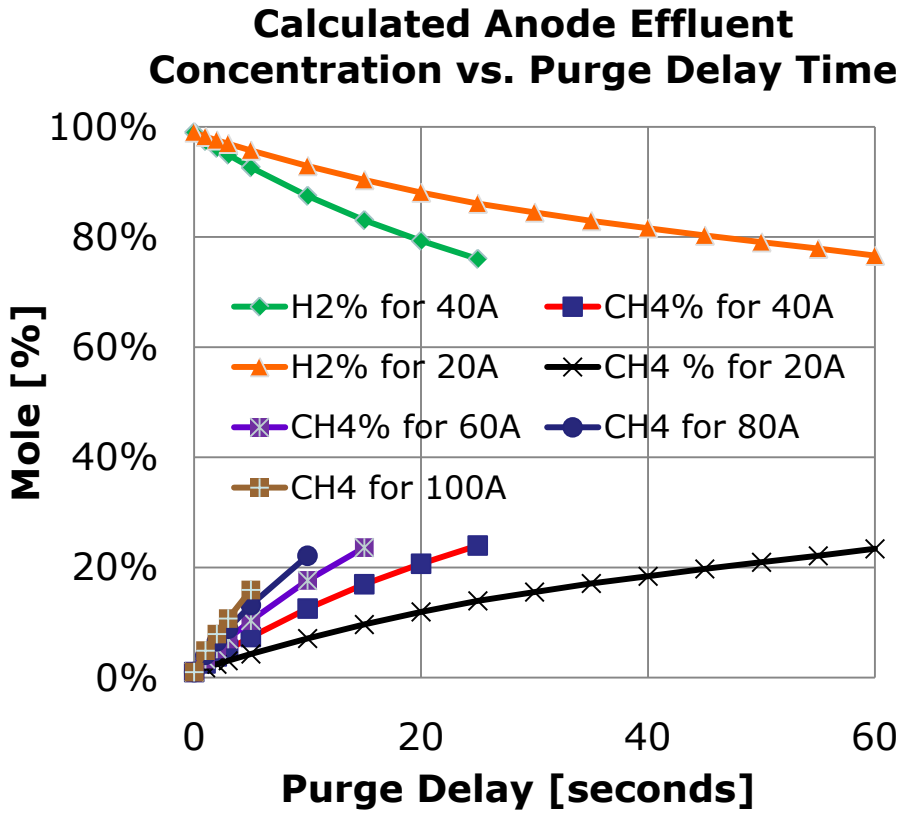
CHP Technical Accomplishments
Twin Stack Development



- **Twin stack system improves efficiency (up to 59% vs. 53% for single stack)**
  - Same platform as automotive systems to benefit from economies of scale
  - Higher voltage output to enable grid-tie via a commercially available PV inverter without a DC/DC boost converter
  - May extend life – to be confirmed in future testing
  - Less back pressure allows for blower with smaller motor thereby reducing parasitic demand

CHP Technical Accomplishments
Stack Testing with 99% Hydrogen [Task 4]





- Decreasing hydrogen purity can increase overall system efficiency
- 99% hydrogen feed yields negligible stack performance penalty

- Decreased purging interval (1-2 seconds less) required for running with 99% hydrogen will not result in system fuel loss: goes on to provide heat of combustion for upstream reforming

Technology Transfer

- Additional investment beyond DOE program to establish strong CHP presence in the UK/IRE market
  - Joint venture with Scottish and Southern Energy
  - System installer and maintenance subcontractor Logan Energy
  - Site modeling and controls subcontractor Element Energy
  - Technology Strategy Board
- California State Polytechnic University Pomona
  - Helping develop future professionals who will possess knowledge of green technologies

Future Work

Field Demonstration in Partnership with Scottish & Southern Energy and DOE

- Six month field demonstration in IPHE country (2011)
- "Greenwatt Way" - former location of SSE office building located 40 miles southwest of London
- Eight dwellings now fully occupied
- Site received NEPA determination in July 2010
- Logan Energy to provide installation and system maintenance support
- SHM will relay real-time data back to IE Knowledge Center
- Energy store will showcase ground-source heat pump, biomass boiler, PV and CHP systems
- AER fuel processor scale up and testing-proposal submitted under DOE FOA-0000360

Summary

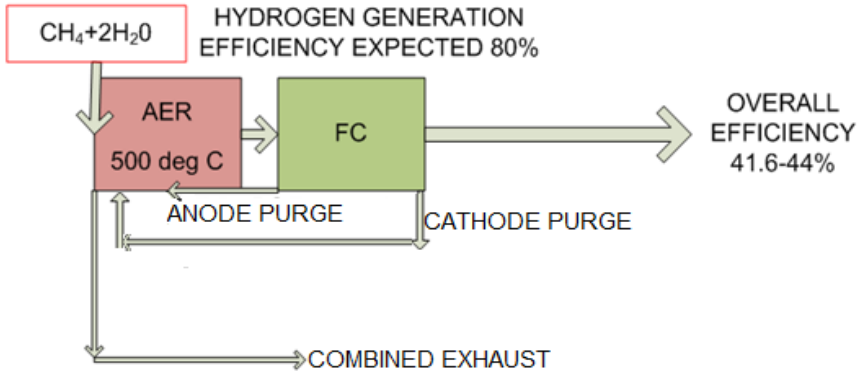
- 2011 field demonstration of system carrying the CE mark
  - Approximately 30% smaller than prototype
  - Projected system electrical efficiency increased to 37%
  - Use of higher efficiency twin stack configuration with additional long-term cost benefit
- 2011 testing of fuel cell stacks with 99% hydrogen showing no adverse impact to efficiency
  - Allows for the evaluation of system level trade off between FCS and H_2 generation processes to maximize performance
- Strong corporate commitment to CHP markets and technology development
  - Joint venture with Scottish and Southern Energy
- 2012/13 development of integrated AER+FC CHP system with the potential to achieve 40% electrical efficiency, ~$750/kW and 40,000 hours durability


www.intelligent-energy.com
Clean power anywhere
Thank You

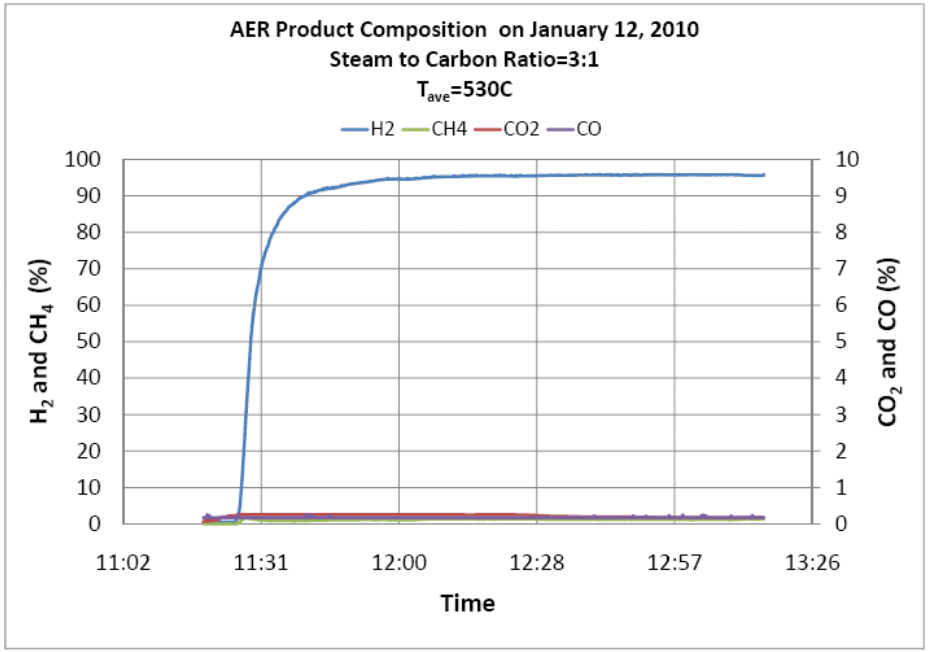
Technical Backup Slides

AER-Boosting H2 Generation Efficiency

- Uses medium temperature (475-550C) and hydrotalcite for CO_2 capture with FC cathode and anode off-gases for regeneration
- Higher Efficiency
- Lower Rx Heat (140 kJ/mol)
- No Water Gas Shift or PSA-lower cost
- Low pressure operation–lower parasitic losses



$$CH_4+2H_20 \rightarrow CO_2(Adsorbed)+4H_2$$



AER Technical Accomplishments

- Summary
  - ➢ High purity hydrogen production achieved
  - ➢ Over 350 hours on test rig
  - ➢ Materials stability indicated
    - >2,500 process cycles switching from production to regeneration back to production
  - ➢ Process simplicity demonstrated (automated operation with PLC and timed solenoid valves- single operator)

Homogenous catalyst/sorbent extrudate

Adsorbent and Catalyst Before

After slight discoloration with no conversion deterioration or breakage

Cautionary Statement with Respect to Forward-Looking Statements

This presentation contains forward-looking statements that reflect Intelligent Energy's plans and expectations. These forward-looking statements are not guarantees of future performance and involve known and unknown risks, uncertainties and other factors that may cause Intelligent Energy's actual results, performance, achievements or financial position to be materially different from any future results, performance, achievements or financial position expressed or implied by these forward-looking statements. These factors include: (i) changes in economic conditions and market demand affecting, and the competitive environment in, the markets in which Intelligent Energy operates; (ii) fluctuations in currency exchange rates, particularly with respect to the value of the Japanese yen, the U.S. dollar, the Euro and the British pound; (iii) Intelligent Energy's ability to realise efficiencies and to implement investments in technologies and other items at the levels and times planned by management; (iv) changes in the laws, regulations and government policies in the markets in which Intelligent Energy operates that affect Intelligent Energy's defence and aerospace, motive, distributed generation and portable and oil and gas target market segments, particularly laws, regulations and policies relating to trade, environmental protection, emissions, fuel economy and safety, as well as changes in laws, regulations and government policies that affect Intelligent Energy's business including the outcome of future litigation and other legal proceedings; (v) political instability in the markets in which Intelligent Energy operates; (vi) Intelligent Energy's ability to timely develop and achieve market acceptance of new products and technologies; and (vii) fuel shortages or interruptions in transportation systems, labour strikes, work stoppages or other interruptions to, or difficulties in, the employment of labour in the major markets where Intelligent Energy and its partners purchases materials, components and supplies for its products, programmes and technologies or where its products, programmes and technologies are produced, distributed or sold.