Spring 4-12-2016

Electrochemical membrane technology for carbon dioxide capture from flue gas

Hossein Ghezel-Ayagh
FuelCell Energy Inc, hghezel@fce.com

Stephen Jolly
FuelCell Energy Inc

Dilip Patel
FuelCell Energy Inc

William Steen
AECOM Corporation

FuelCell Energy

Ultra-Clean, Efficient, Reliable Power

Electrochemical Membrane Technology for CO_2 Capture from Flue Gas

Stephen Jolly, Hossein Ghezel-Ayagh, and William A. Steen

CO_2 Summit II: Technologies and Opportunities

April 10–14, 2016

Santa Ana Pueblo, New Mexico, USA

Ultra-Clean | Efficient | Reliable Power

FuelCell Energy
Ultra-Clean, Efficient, Reliable Power

Integrated Fuel Cell Company

Research & Development

- *Global fuel cell technology platform*
- *Robust intellectual property portfolio*
- *Leveraging core technology for new market opportunities*

Sales, Manufacture & Project Execution

- *Project development – Direct Sales*
- *Global manufacturing (200+ MW capacity)*
- *Engineering, Procurement and Construction*

Services

- *Operate & Maintain power plants*
- *100+ DFC® plants operating at 50+ sites globally*
- *>4 billion kWh ultra-clean power produced*
- *> 300 MW installed/backlog*

1.4 MW power plant

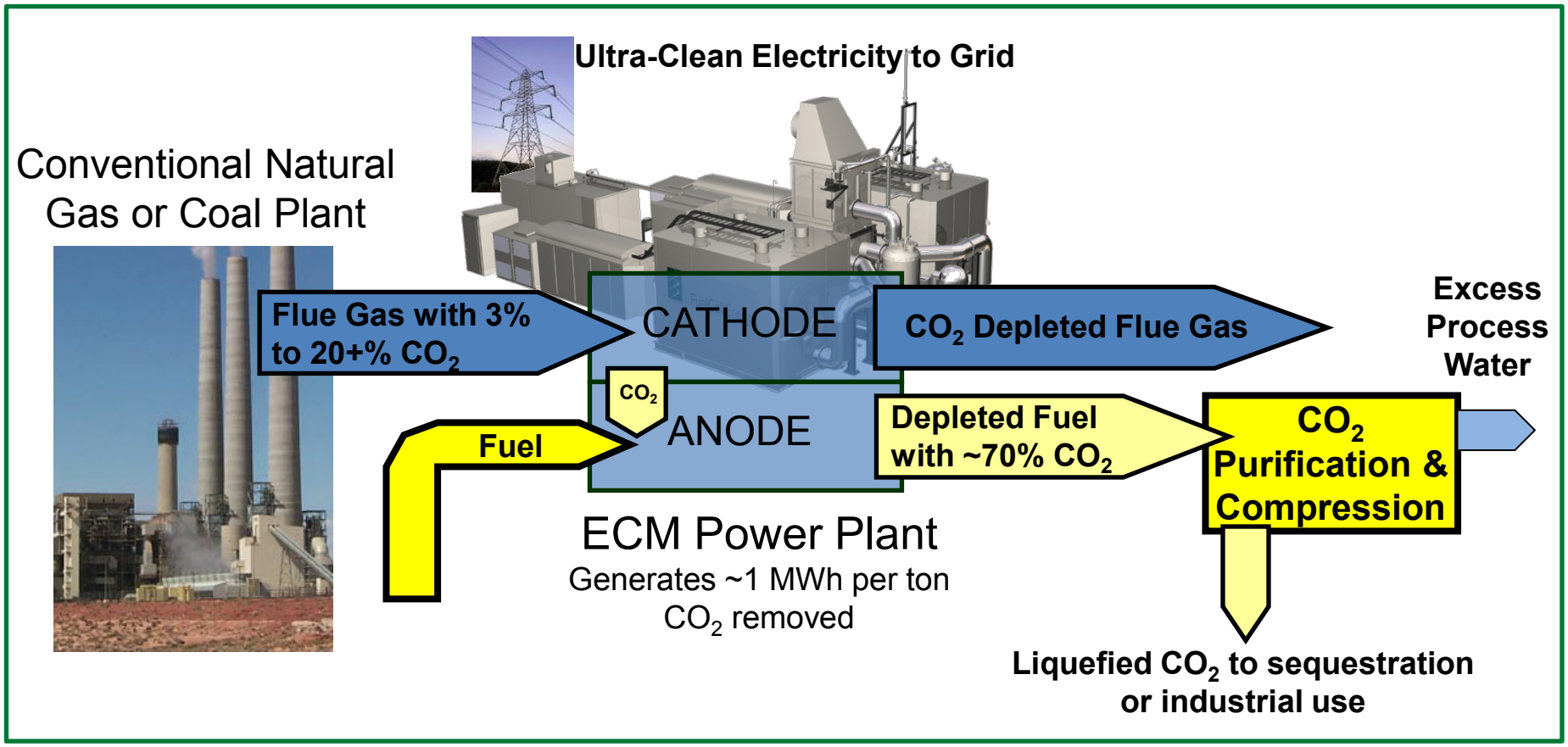
11.2 MW fuel cell system

2.8 MW power plant

5 unit fuel cell park

FuelCell Energy
Ultra-Clean, Efficient, Reliable Power

Electrochemical Membrane (ECM) for CO_2 Capture

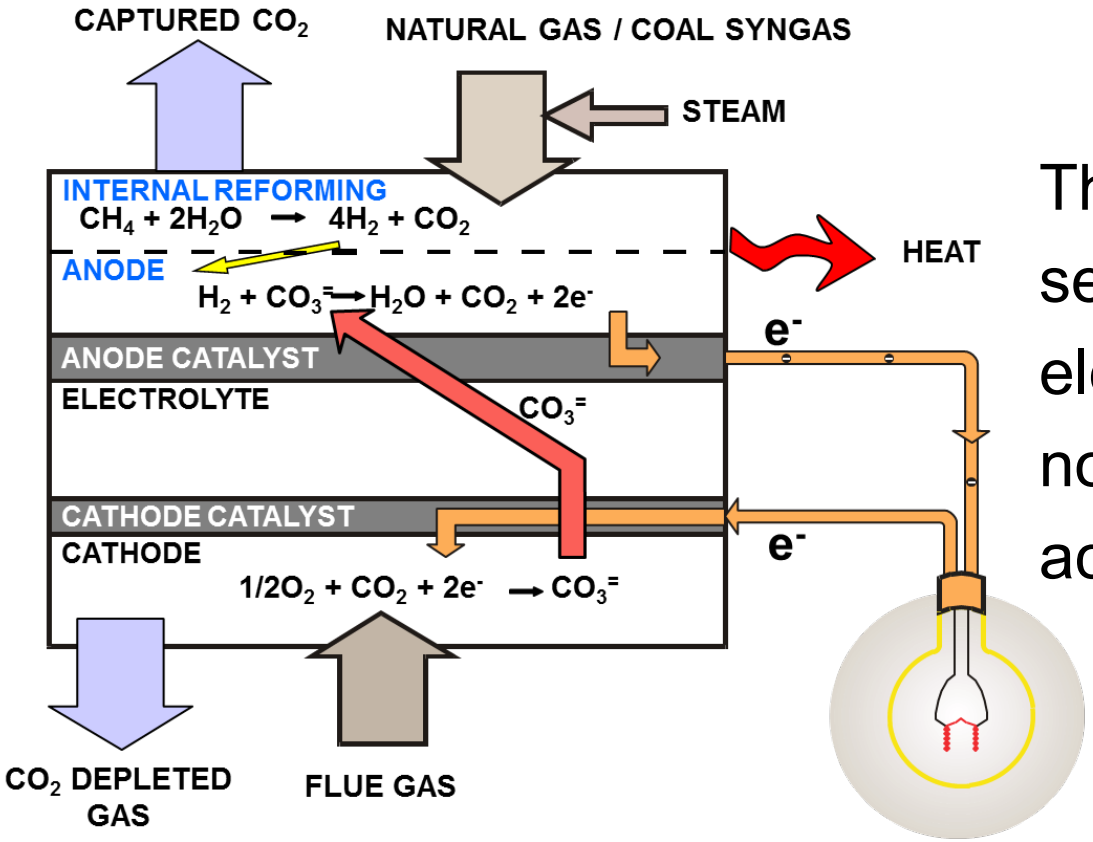


Net Results

- Re-application of commercially-proven DFC® technology as Electrochemical Membrane for CO_2 Capture
- Simultaneous Power Production and CO_2 Separation from Flue Gas of an Existing Facility
- Excess Process Water Byproduct

FuelCell Energy
Ultra-Clean, Efficient, Reliable Power

Electrochemical Membrane Technology

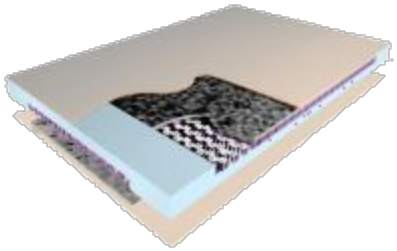


The driving force for CO_2 separation is electrochemical potential, not pressure differential across the membrane

- ECM offers complete selectivity towards CO_2 as compared to N_2
- Fast electrode kinetics at 600°C operating temp. make ECM suitable for flue gases with <15% CO_2, typical of coal or gas-fired plants
- Due to the planar geometry and large gas flow channels, ECM can process large gas volumes without significant back pressures (5-8 cm of water)

FuelCell Energy
Ultra-Clean, Efficient, Reliable Power

Modular Technology



ECM Assembly

ECM Stack (Using 400 ECM Assemblies)

ECM Module (4 Stacks)

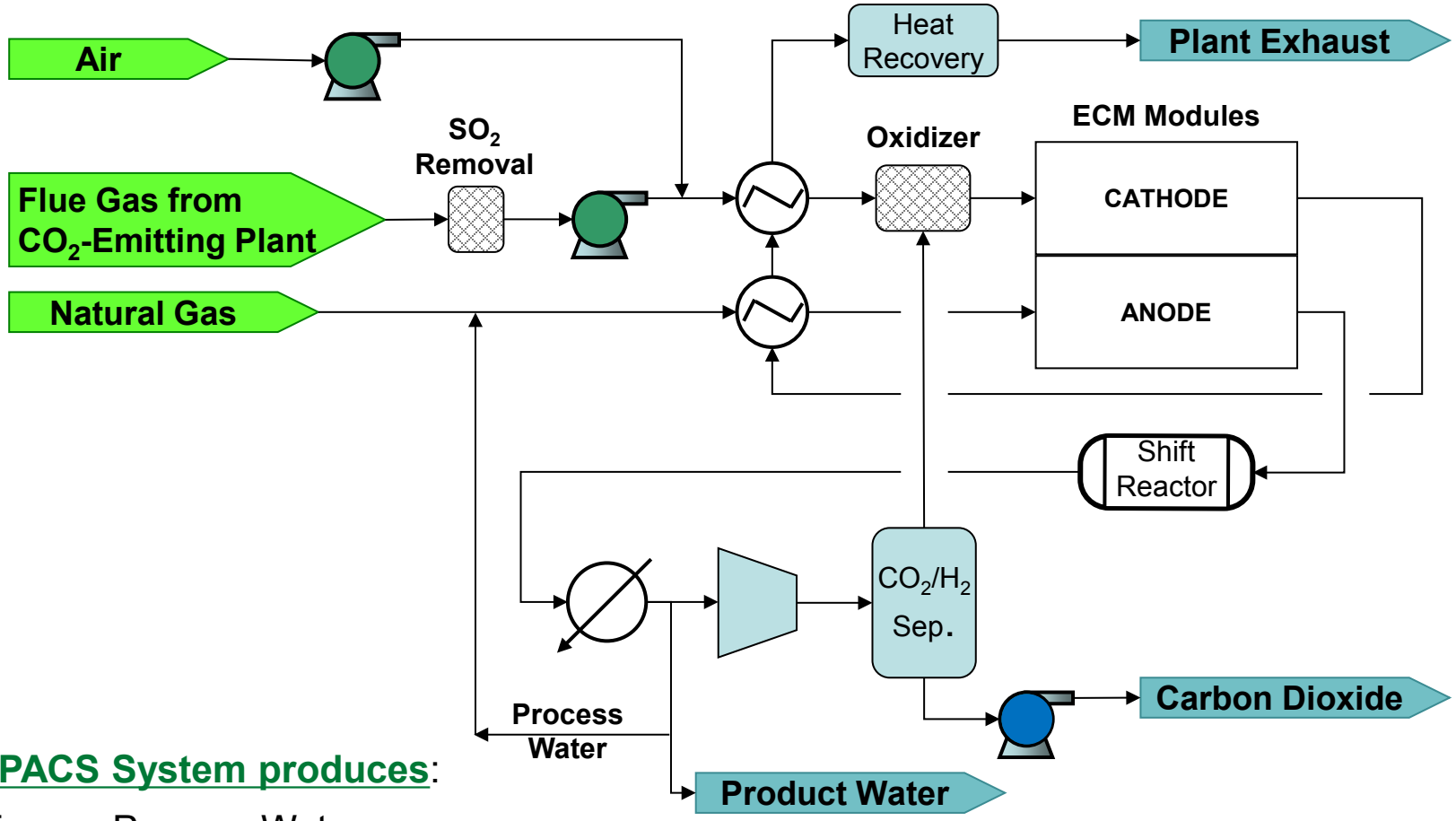
Enclosed Module

Modules Utilized in Large-Scale Applications

FuelCell Energy
Ultra-Clean, Efficient, Reliable Power

System Block Diagram

Combined Electric Power and Carbon-dioxide Separation (CEPACS) System



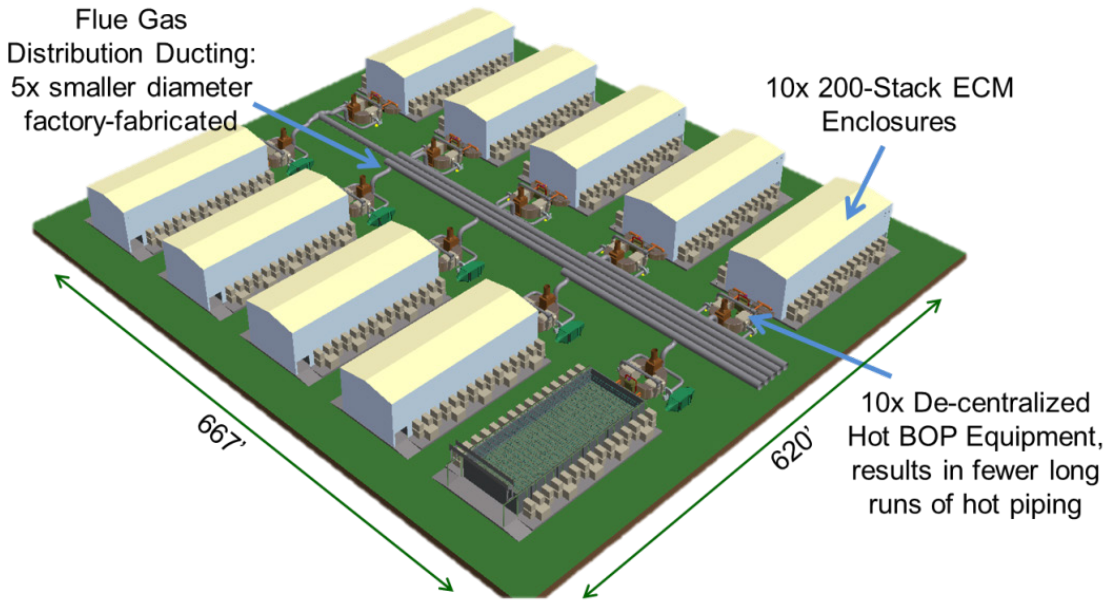
CEPACS System produces:

- Excess Process Water
- Supercritical CO_2 (90% CO_2 capture from PC Plant)
- Additional clean AC power

FuelCell Energy
Ultra-Clean, Efficient, Reliable Power

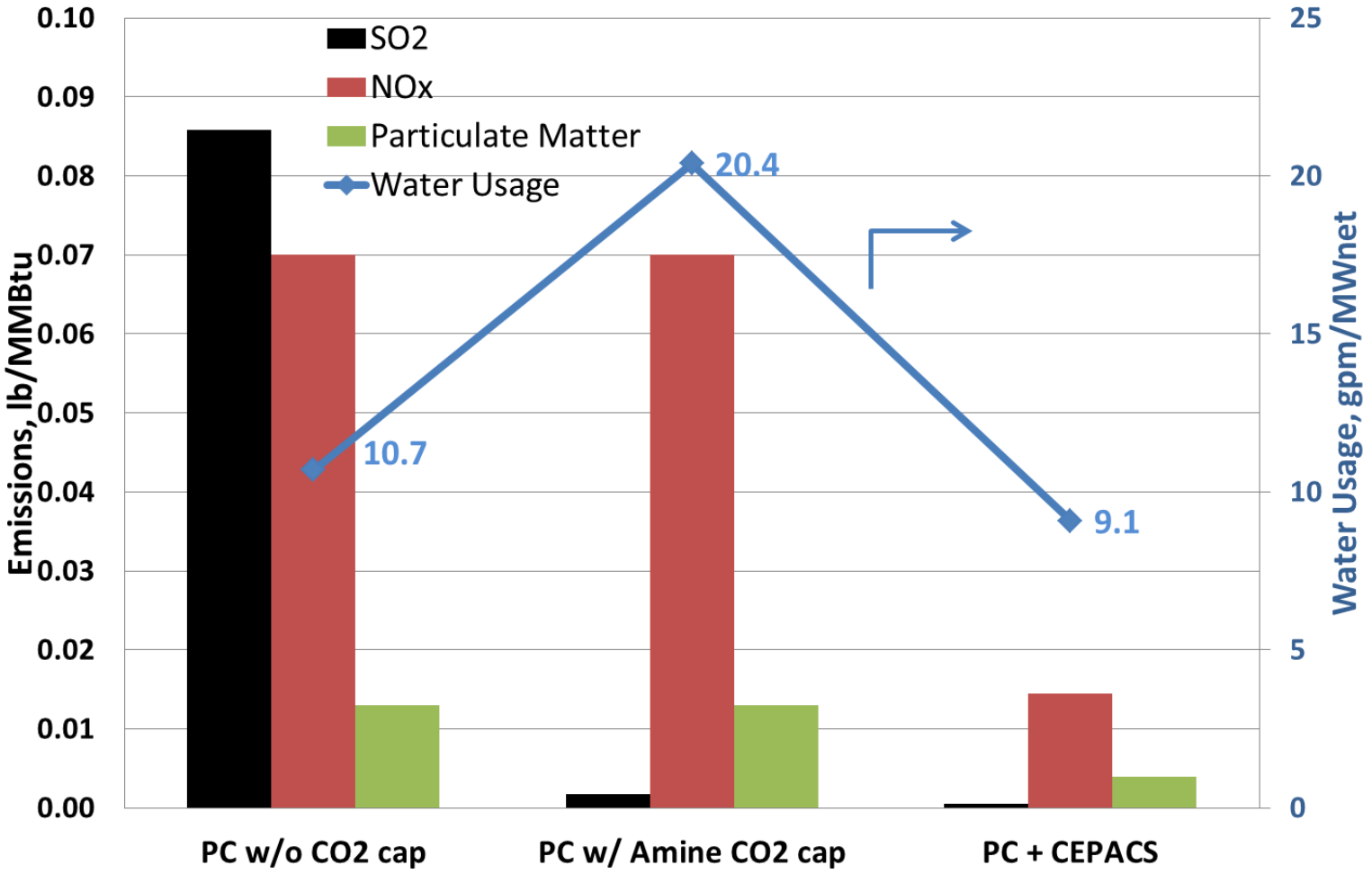
Coal Power Plant Application

- **420MW ECM-based system would capture 90% of CO_2 from 550MW Pulverized Coal (PC) plant**
- 4.9 Million tons of CO_2 capture per year
- 3.2GWh ultra-clean power generated per year
- System designed for achieving high availability (>90%) for capture from large scale coal plants
- Cost of CO_2 captured less than $40/ton, or less than $0.02/kWh



FuelCell Energy
Ultra-Clean, Efficient, Reliable Power

Emissions and Water Usage



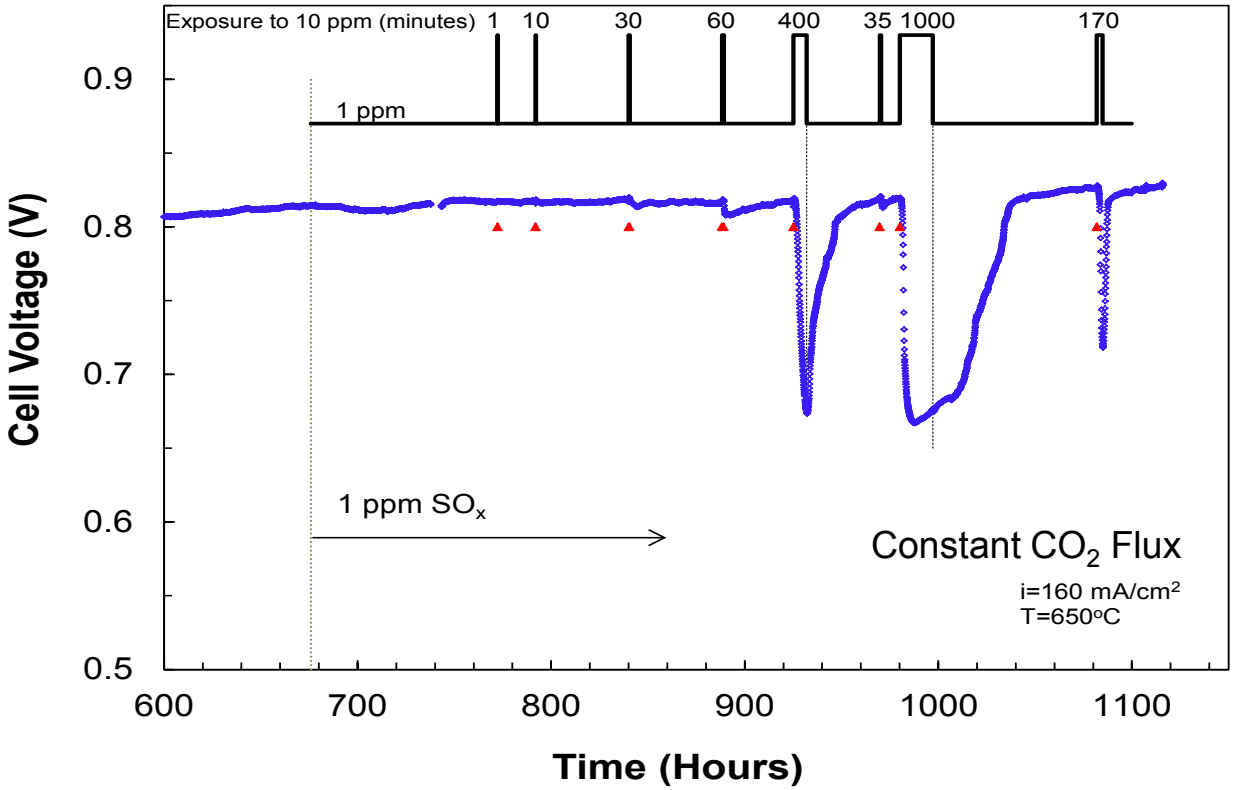
- PC plant retrofitted with CEPACS system has lower emissions of NOx, SOx, and Hg than a PC plant retrofitted with Amine scrubber for CO_2 capture
- CEPACS system produces excess process water, reducing the total plant water usage

FuelCell Energy
Ultra-Clean, Efficient, Reliable Power

ECM Flue Gas Contaminant Tolerance: SO_2

To simulate flue gas cleanup system upsets, ECM response to spikes of SO_2 concentrations was studied:

Pacific Northwest
NATIONAL LABORATORY



- ECM performance is stable using a polishing equipment which reduces upstream SO_2 concentration in the flue gas (cathode gas) to <1 ppm
- Performance loss was fully recoverable after exposing ECM to 10 ppm transients SO_2 of varying lengths with recovery time proportional to length of transient

FuelCell Energy
Ultra-Clean, Efficient, Reliable Power

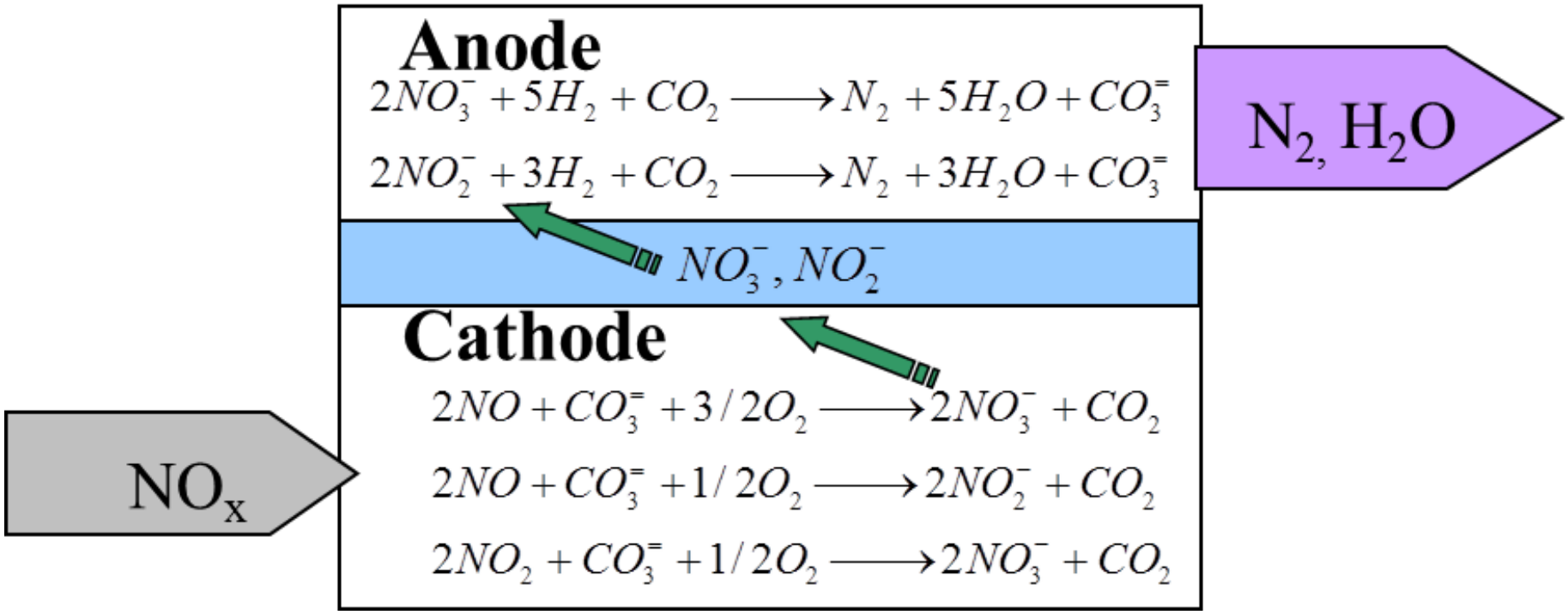
ECM Flue Gas Contaminants Tolerance: Summary

Flue Gas Contaminant	Concentration in Cathode Inlet Gas After Polishing FGD, Estimated by AECOM		Highest Concentration Tested by PNNL, with low/no power degradation		Notes
SO_2	**0.18**	**ppmv**	**1**	**ppmv**	Performance losses due to short-term SO_2 exposure up to 40ppm were fully reversible
Se	**0.30**	**ppbv**	**10**	**ppbv**	No apparent degradation over 860 hours.
Hg	**0.08**	**ppbv**	**250**	**ppbv**	Expected form is predominantly elemental Hg. No apparent degradation over 1100 hours.
HCl	**12.7**	**ppbv**	**200**	**ppbv**	No apparent degradation over 900 hours.

- Based on PNNL testing and AECOM performance estimates, a polishing wet-FGD scrubber is designed to sufficiently clean flue gas for ECM operation

ECM NO_x Removal Mechanism

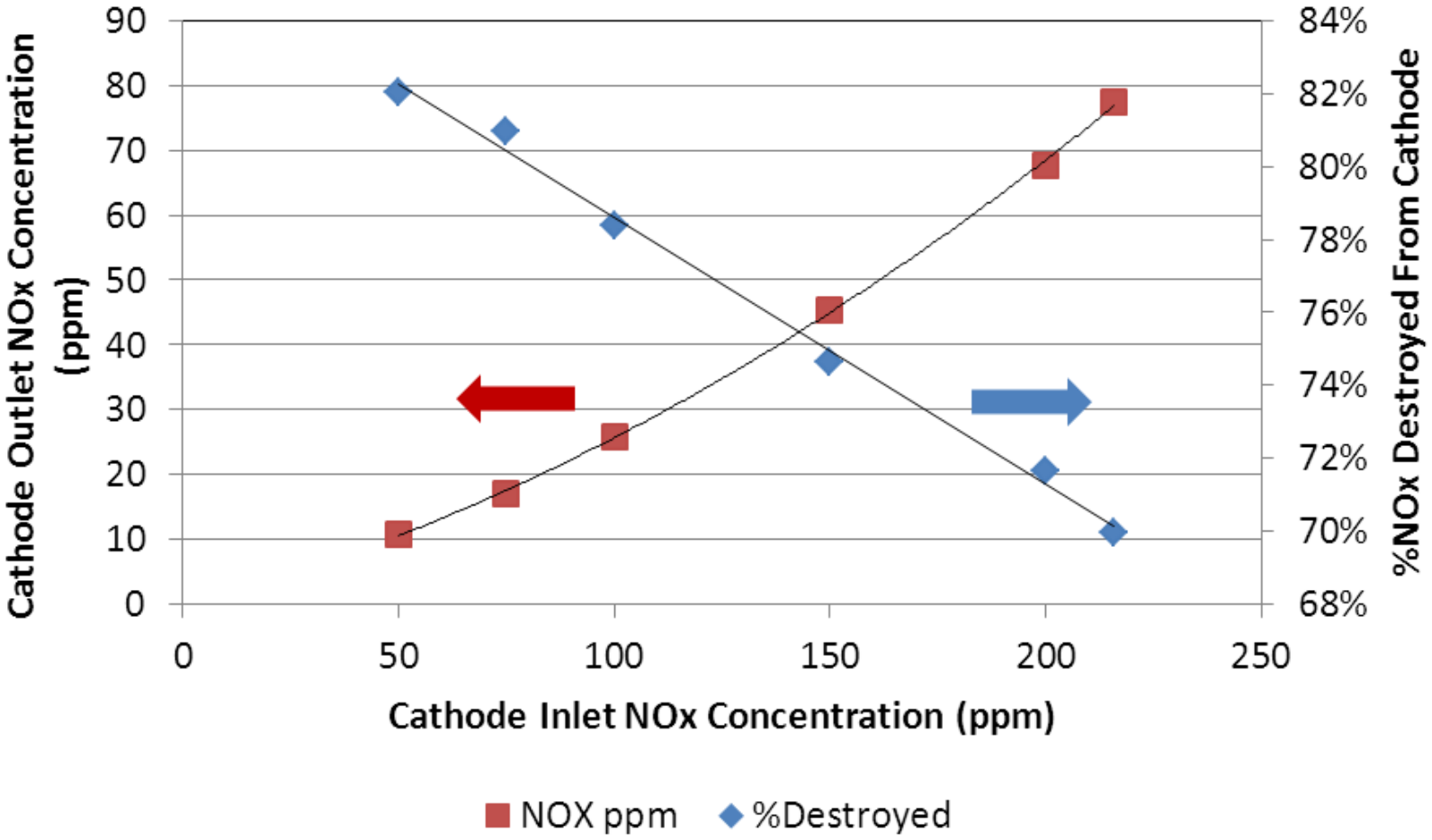
- Based on FCE's prior experience:
  - ECM materials are not expected to be degraded by NOx in flue gas
  - CEPACS system offers co-benefit of NOx reduction



Reaction Mechanism by which NOx is removed from the Flue Gas (cathode-side), transferred to the anode-side along with CO_2, and subsequently destroyed

FuelCell Energy
Ultra-Clean, Efficient, Reliable Power

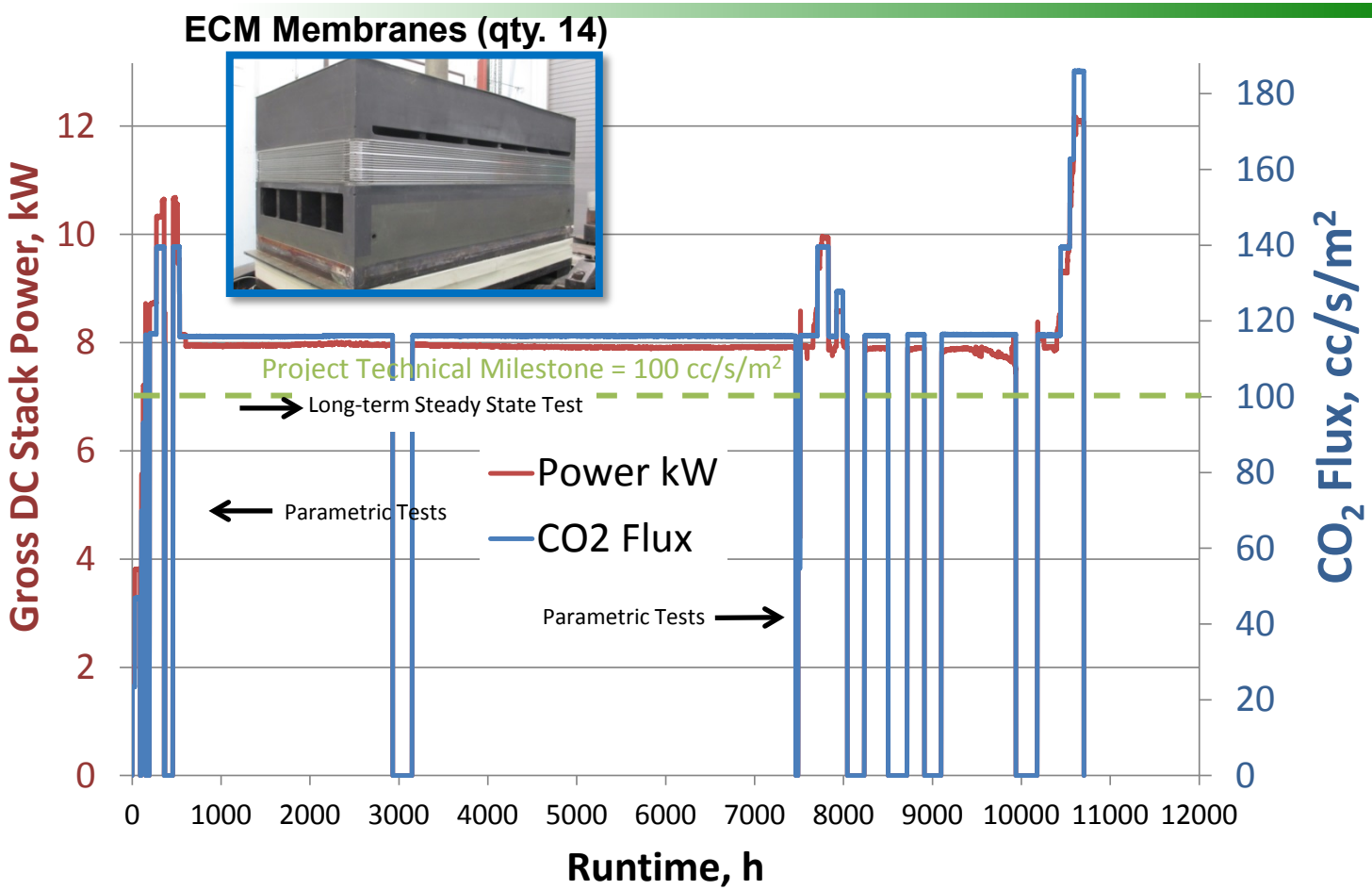
ECM NO_x Removal Capabilities



- ECM Capability for NO_x Destruction Remains > 70% at High Inlet NO_x Concentration (200 ppm) During Carbon Capture under System Conditions

FuelCell Energy
Ultra-Clean, Efficient, Reliable Power

Bench-Scale Demonstration

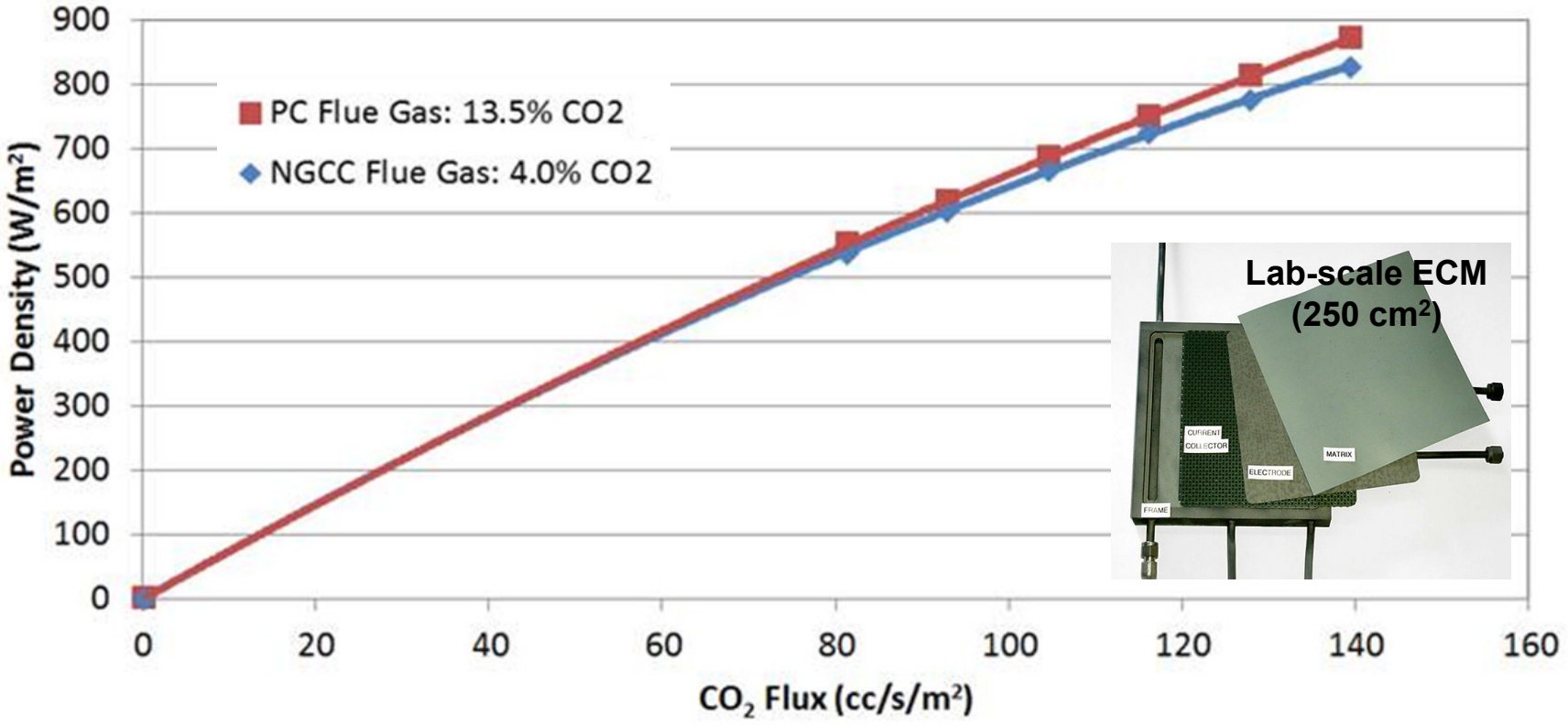


CEPACS demonstration system for PC flue gas currently undergoing testing at FCE:

- 100 tons/year liquid CO_2 product
- >10 kW peak power production
- Bench-scale CEPACS test results verified high CO_2 flux and stable operation for >10,000 hours

ECM Performance: Effect of Flue Gas Composition

ECM cell performance data for NGCC and PC plant flue gases at 93% carbon capture:

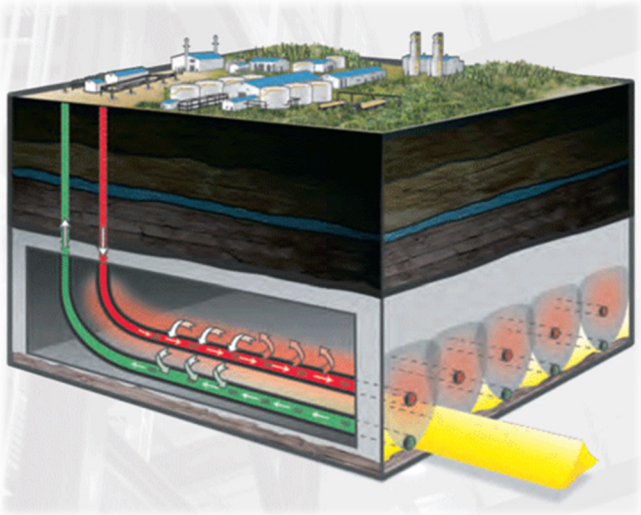


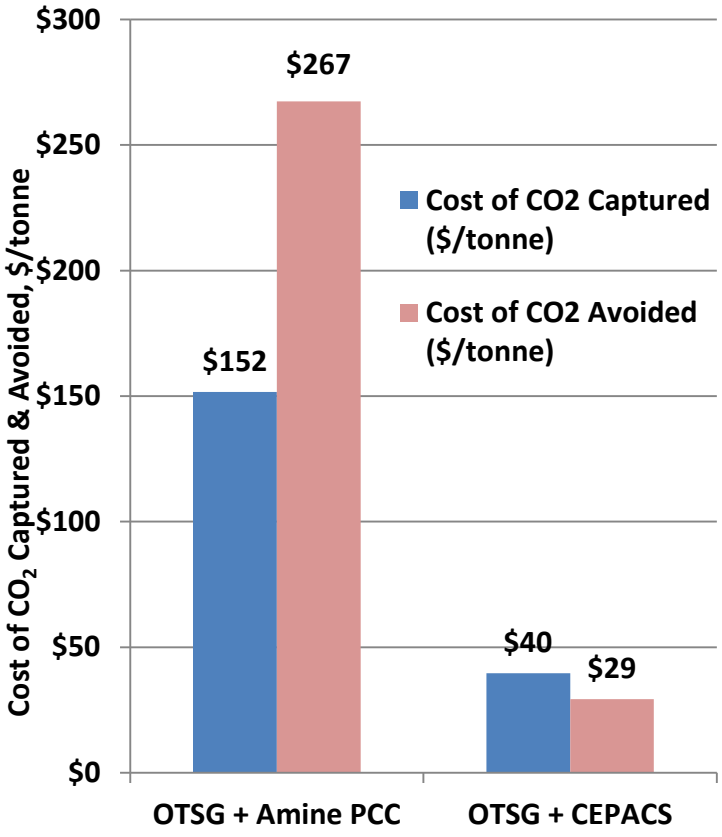
- Due to fast electrode kinetics, ECM is capable of operating on flue gases with a wide range of CO_2 partial pressure:
  - Pulverized coal-fueled boilers
  - Natural gas-fueled boilers
  - Natural gas turbine and combined cycle plants

FuelCell Energy
Ultra-Clean, Efficient, Reliable Power

Case Study: ECM for CO_2 Capture from SAGD Bitumen Extraction

Jacobs Consultancy developed an independent analysis* of an ECM system for 90% CO_2 capture applied to a 33,000 BOPD Steam Assisted Gravity Drainage (SAGD) facility under a study by Alberta Innovates (Alberta, Canada)





ECM system:

- Captures 90% of CO_2 from SAGD NG-fired Once Through Steam Generator (OTSG)
- Produces 62 MWe net, enough to cover all SAGD power requirements and export 48 MWe
- Reduces SAGD facility makeup water requirements by 44% (compared to without CCS)

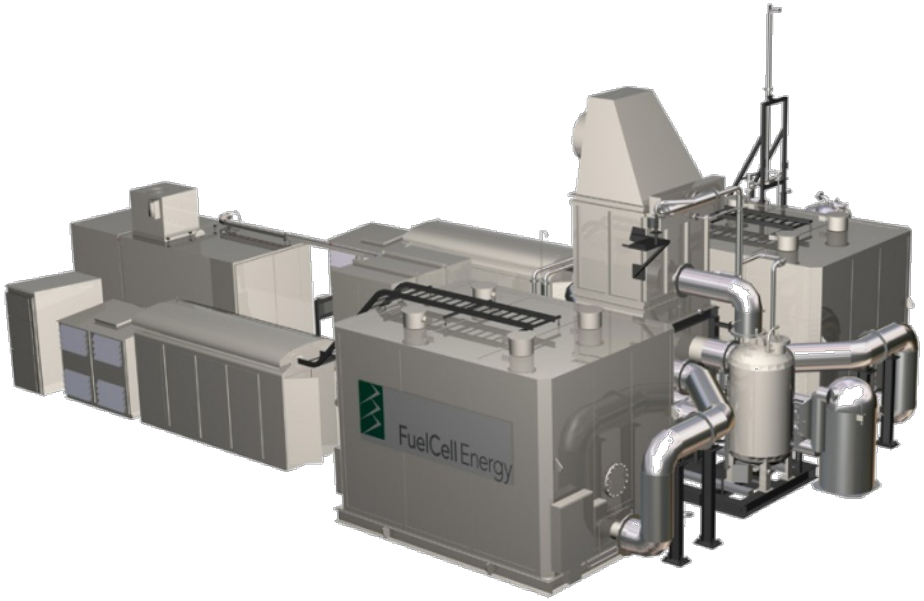
Alberta Innovates Energy and Environment Solutions

*available: http://www.ai-ees.ca/media/14423/ecm_evaluation_study_report-final_all.pdf

FuelCell Energy
Ultra-Clean, Efficient, Reliable Power

Pilot –Scale Project

- Recently awarded Co-operative Agreement with DOE (DE-FE0026580)
- Pilot ECM system to capture >90% of CO_2 from a 3 MWe equivalent slipstream of a PC plant flue gas
- Objective to confirm high purity (>95%) CO_2 capture with a cost of electricity <30% of state-of-the-art capture technologies in large-scale applications
- 42 months project starting 10/1/2015
- Host site selection underway



Pilot-Scale Project:
Designed to capture **>58 tons CO_2 per day** while simultaneously producing **>1.5 MW** of ultra-clean electricity

FuelCell Energy
Ultra-Clean, Efficient, Reliable Power

ECM Carbon Capture Summary

Captures and Concentrates exhaust from
- Coal power plant
- Natural gas power plant
- Industrial process

Proven Technology
- Leverages commercial fuel cell technology
- Project underway to demonstrate MW-class pilot plant for capture from coal flue gas

Economical
- Produces additional power vs power reduction
- Generates return on capital vs operating expense

Additional Benefits
- 70% reduction in NOx
- Clean water production

Fuel Cell Manufacturing Facility, Torrington, CT

Hwaseong, South Korea 59 MW Fuel Cell System

Acknowledgements

ECM Carbon Capture from Coal Plants supported by DOE/NETL (Co-operative Agreements: DE-FE0007634 & DE-FE0026580)

Guidance from NETL team: José Figueroa, Elaine Everitt, Lynn Brickett, John Litynski, and others at NETL/DOE

FuelCell Energy
Ultra-Clean, Efficient, Reliable Power

Thank You

Stephen Jolly
Sr. Manager, Advanced Systems Design
203.830.7519
SJolly@fce.com

FuelCell Energy, Inc.
3 Great Pasture Rd
Danbury, CT 06810
www.fuelcellenergy.com