FuelCell Energy

Ultra-Clean, Efficient, Reliable Power

Electrochemical Membranes for CO_2 Capture and Power Generation

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DE-FE0007634 Project Outline

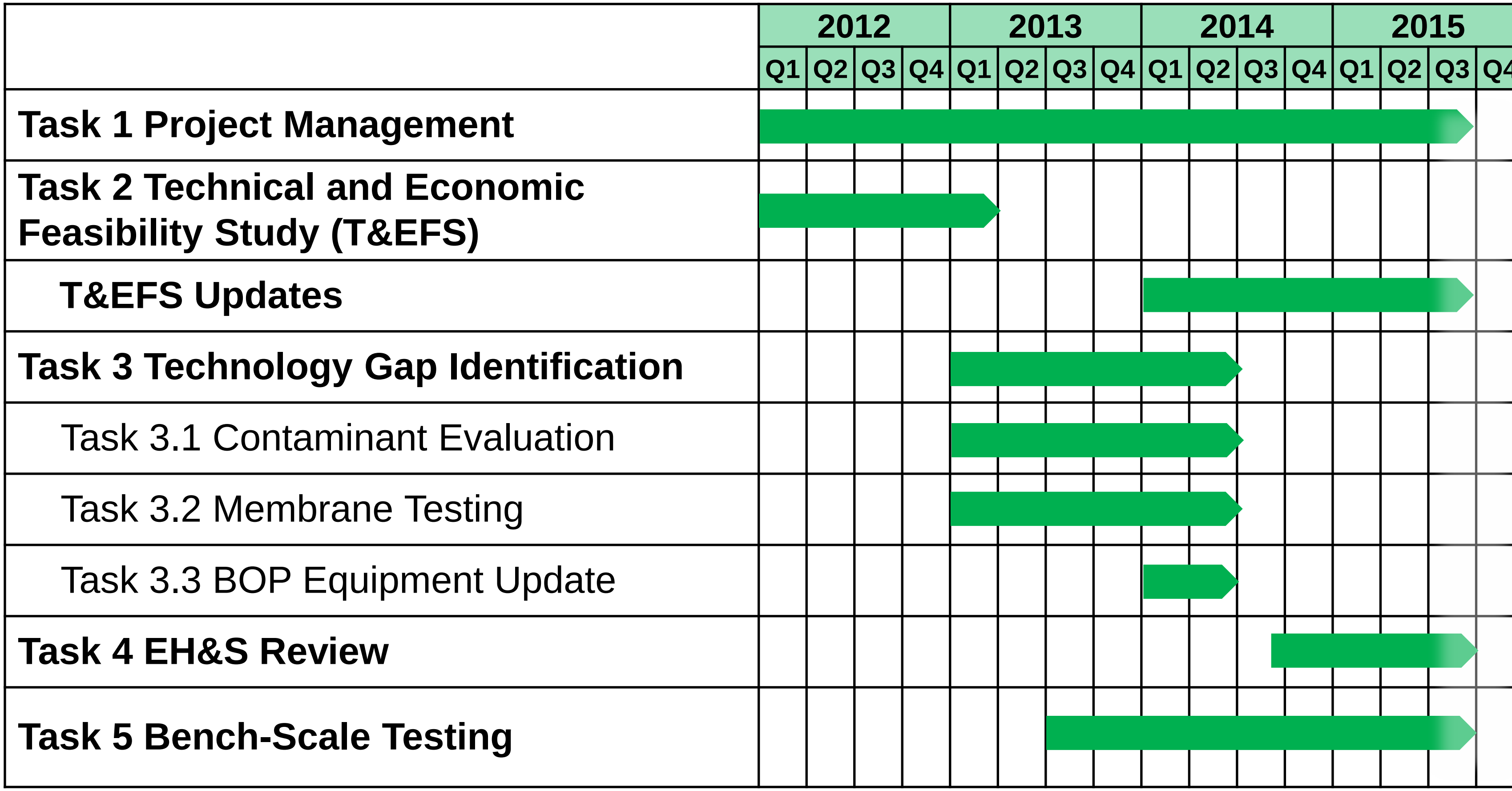
Overall Project Objectives:

- Demonstrate ability of FCE's electrochemical membrane (ECM)-based system to separate ≥ 90% of CO_2 from a simulated PC flue-gas stream suitable for sequestration or beneficial use
- Demonstrate that ECM system is an economical alternative for post-combustion CO_2 capture in PC-based power plants, and that it meets DOE objectives for incremental cost of electricity (COE)

Project Participants:

FuelCell Energy, Inc. (FCE) FuelCell Energy Ultra-Clean, Efficient, Reliable Power	**System design, TEA, Gap analysis, ECM fabrication, and bench-scale testing of an 11.7 m^2 area ECM system for CO_2 capture.**
Pacific Northwest National Laboratory (PNNL) Pacific Northwest NATIONAL LABORATORY	**Test effects of flue gas contaminants on ECM.**
AECOM Technical Services (formerly URS Corporation) AECOM	**Review ECM-based system design, equipment and plant costing, and flue gas clean-up system design.**

Project Tasks, Schedule and Funding

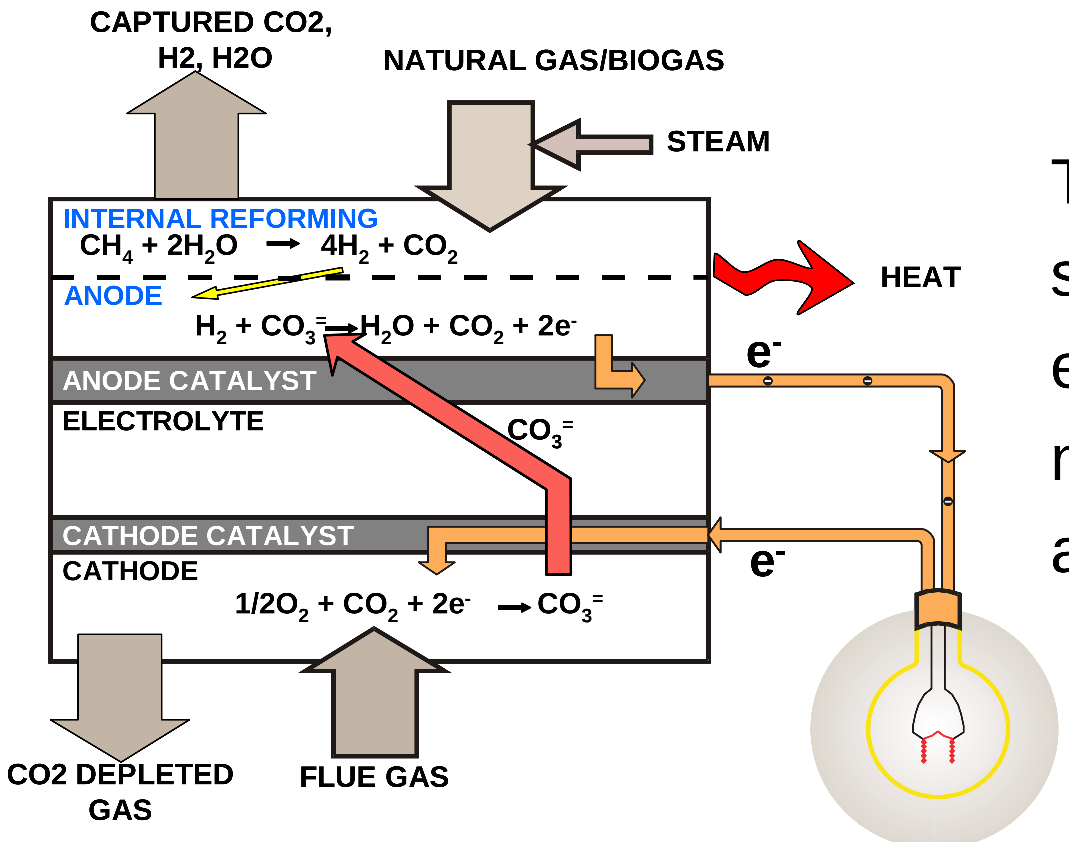


Project Funding		
DOE Share	FCE Cost Share	Project Total
$3,034,106	$758,527	$3,792,633

Project Milestones

Budget Period	Task	Milestone Description	Planned End Date	Actual End Date	Status
1	2.1	Demonstrate the potential of the ECM-based system to achieve 90% carbon capture from the Reference PC Plant, based on results of a system study	5/30/12	3/31/12	✌
1	2.2	Demonstrate potential to achieve incremental COE of <35%	5/30/12	5/30/12	✌
2	3.2	Verify that ECM CO_2 flux can meet the target identified in the Technical and Economic Feasibility Study	7/31/13	12/31/12	✌
2	3.2	Demonstrate >50% NO_x Destruction Capability of ECM	12/13/13	6/30/12	✌
2	3.1	Verify that ECM contaminant tolerances can be met by cost-effective flue gas pretreatment technologies	12/23/13	9/30/13	✌
3	5.4	Verify CO_2 Flux at 100 cc/m^2/s	9/31/14	7/30/14	✌
3	5.4	Complete 9 Months of Endurance testing with degradation in Carbon Capture Efficiency based on the value identified in the Technical and Economic Feasibility Study	6/19/15	5/31/15	✌
3	5.4	Demonstrate 3 deep Thermal Cycles between ambient and operating temperatures with <2% Degradation in Carbon Capture Efficiency	8/16/15		

Electrochemical Membrane (ECM) Technology



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

Net Results

- Simultaneous Power Production and CO_2 Separation from Flue Gas of an Existing Facility
- Excess Process Water Byproduct
- Complete Selectivity towards CO_2 as Compared to N_2

Solutions that Create Value

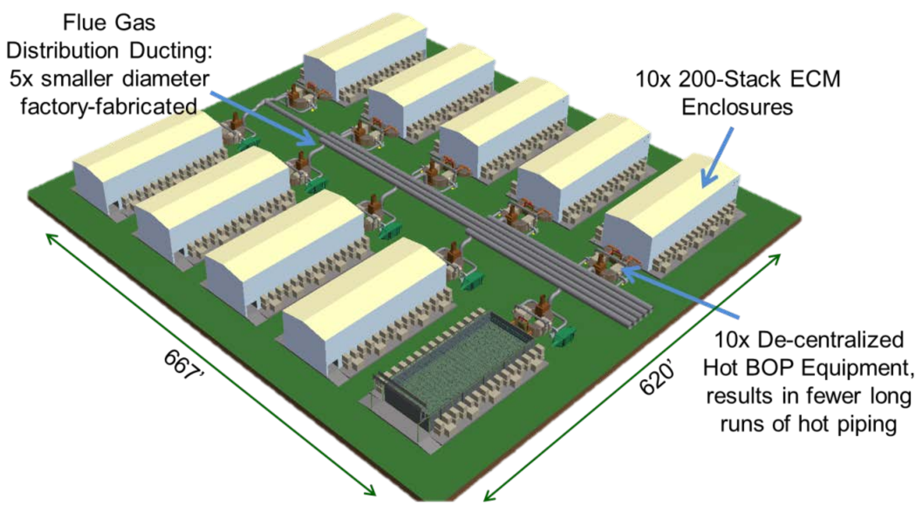
Modular and Scalable Global Solution

- Ease of scale-up and transport
- Suitable for incremental phased applications to almost any type of CO_2-emitting plant
- Proven technology based on FCE's commercial Direct FuelCell® for power generation applications

ECM Assembly

ECM Stack

Four-Stack Module



421MWe CEPACS Plant for >90% Carbon Capture from 550MWe PC Plant

MW-Class Module

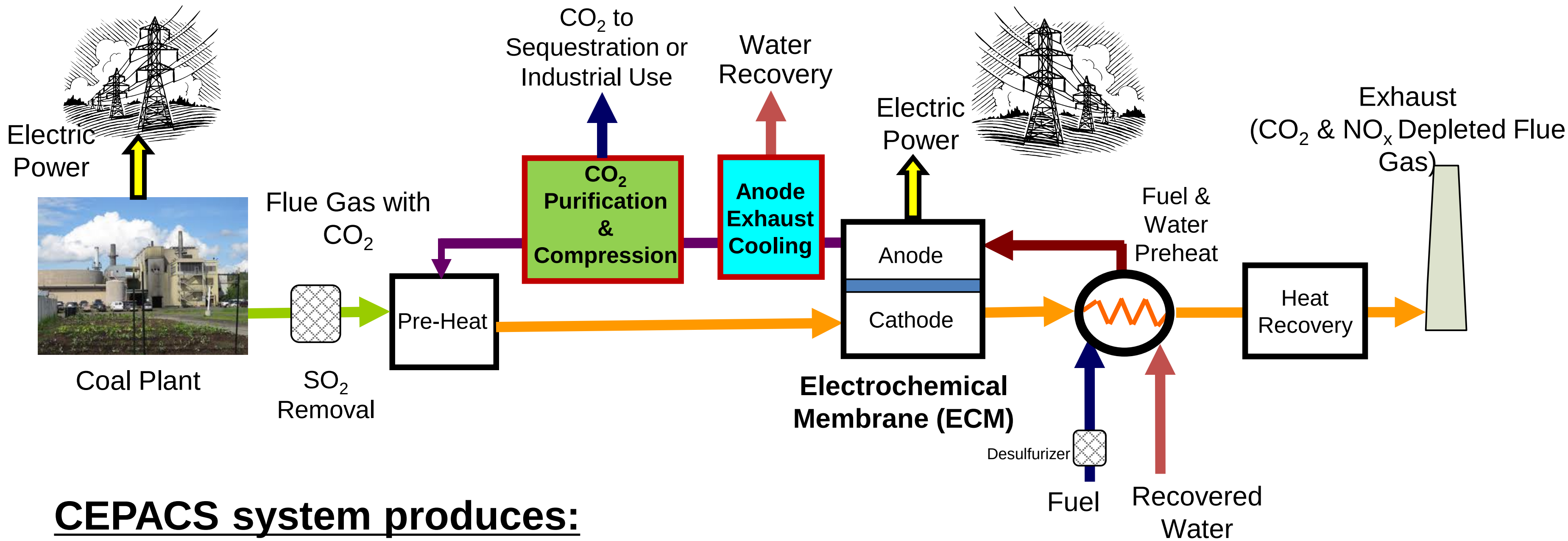
2-Module plant

10-Module Plant

Techno-Economic Analysis

CEPACS System Simplified Block Flow Diagram

Combined Electric Power and Carbon-dioxide Separation (CEPACS) System Concept Implementation for 550 MW Reference PC Plant*



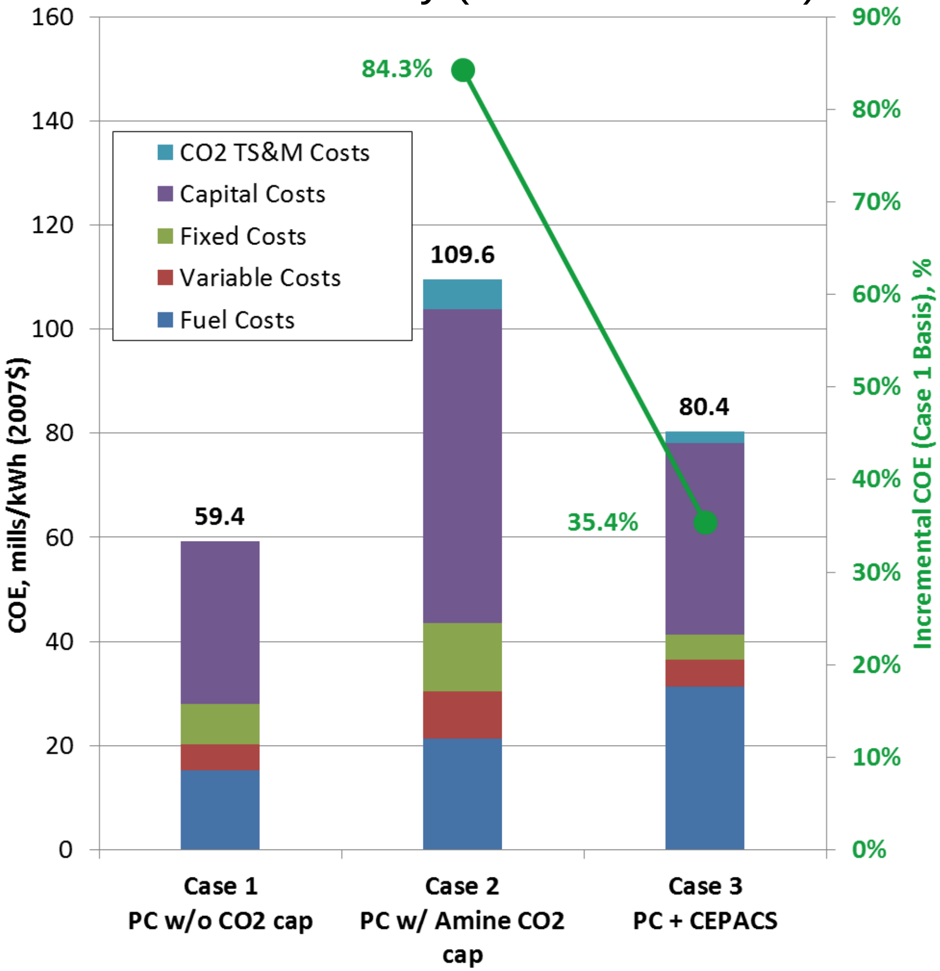
CEPACS system produces:

- Supercritical CO_2 (90% CO_2 capture from PC Plant)
- Excess Process Water
- Additional 421 MW of clean AC power @ 42.4% Efficiency (based on LHV NG)

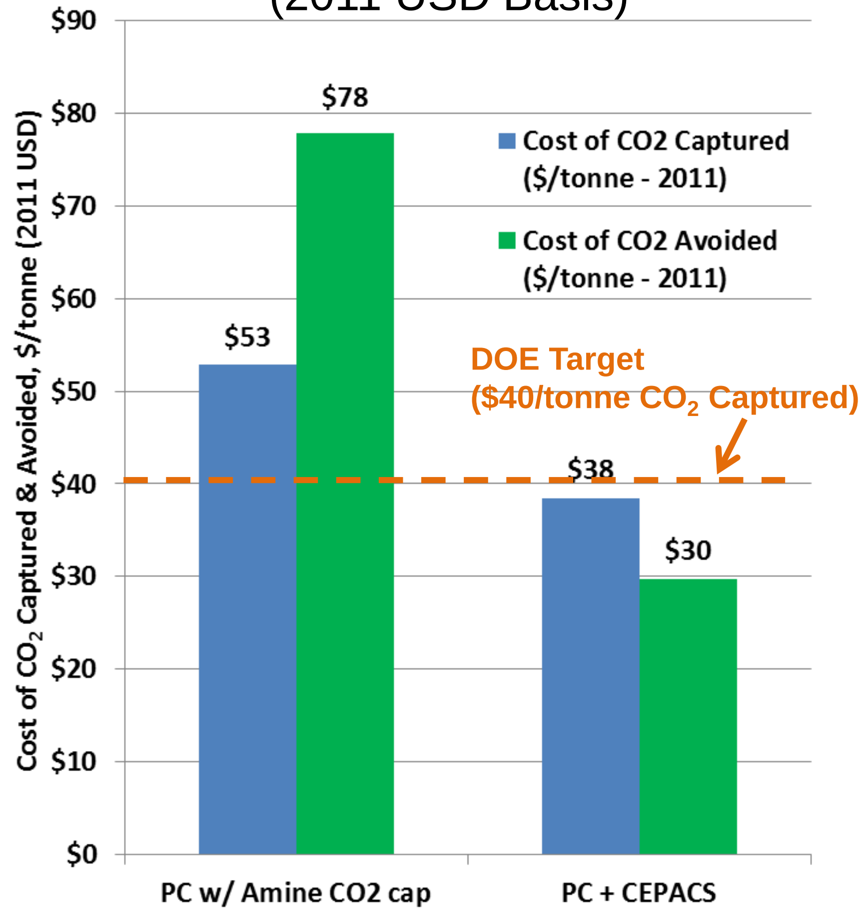
* Cost and Performance Baseline for Fossil Energy Plants, Volume 1: Bituminous Coal and Natural Gas to Electricity, Revision 2, DOE/NETL-2010/1397, November 2010.

Techno-Economic Analysis Results

Cost of Electricity (2007 USD Basis)



Cost of CO_2 Captured & Avoided (2011 USD Basis)



- CEPACS System incremental COE meets DOE target of <35%
- CEPACS System can meet DOE Target of <$40/tonne CO_2 captured (2011 USD)

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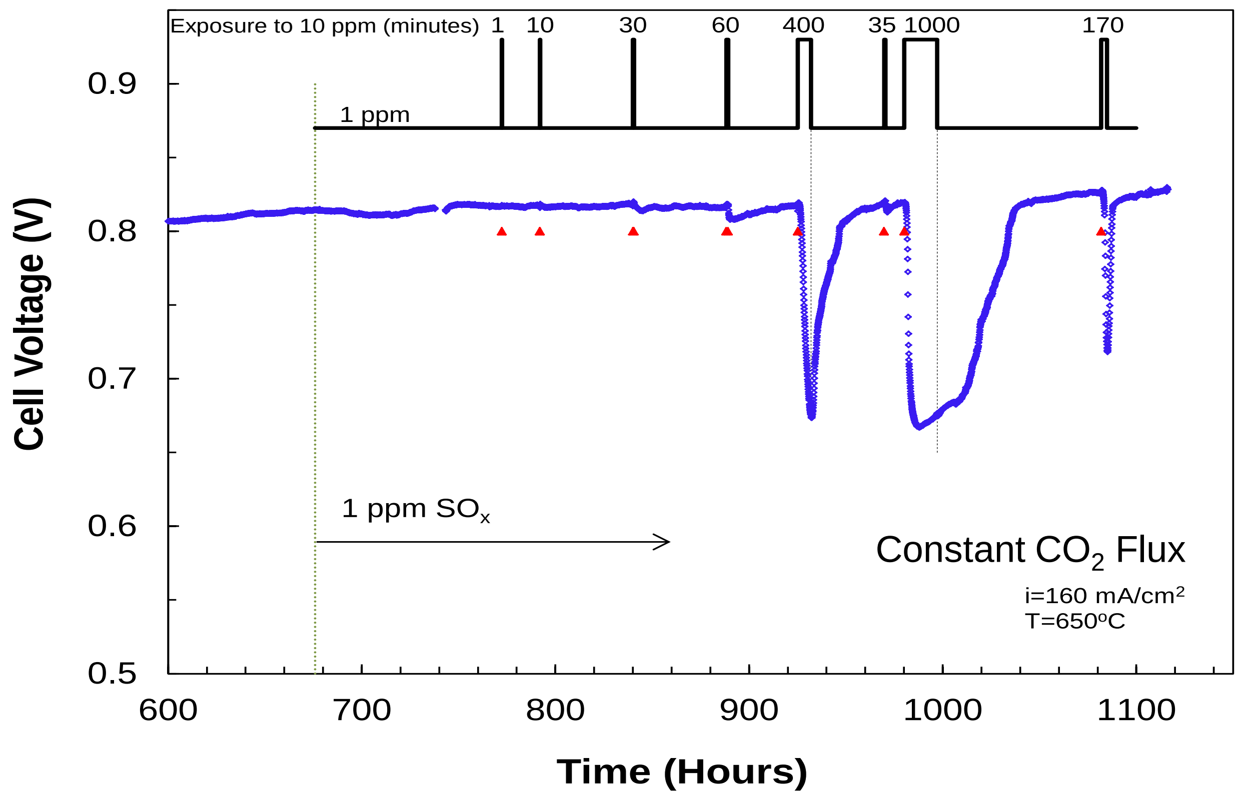
ECM Testing Results

- ***ECM Tolerance to Flue Gas Contaminants***
- ***Bench-scale (11.7m^2) ECM System***

ECM Flue Gas Contaminant Tolerance: SO_2

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



- 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

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

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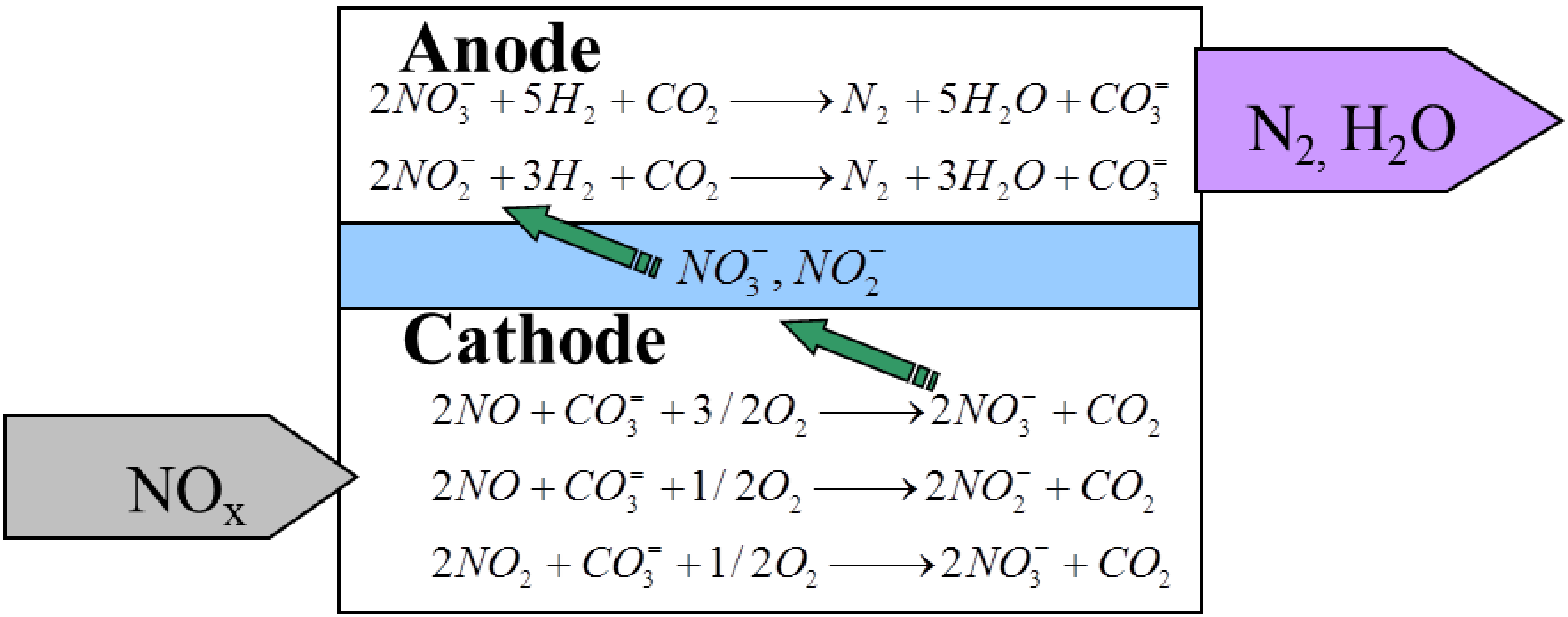
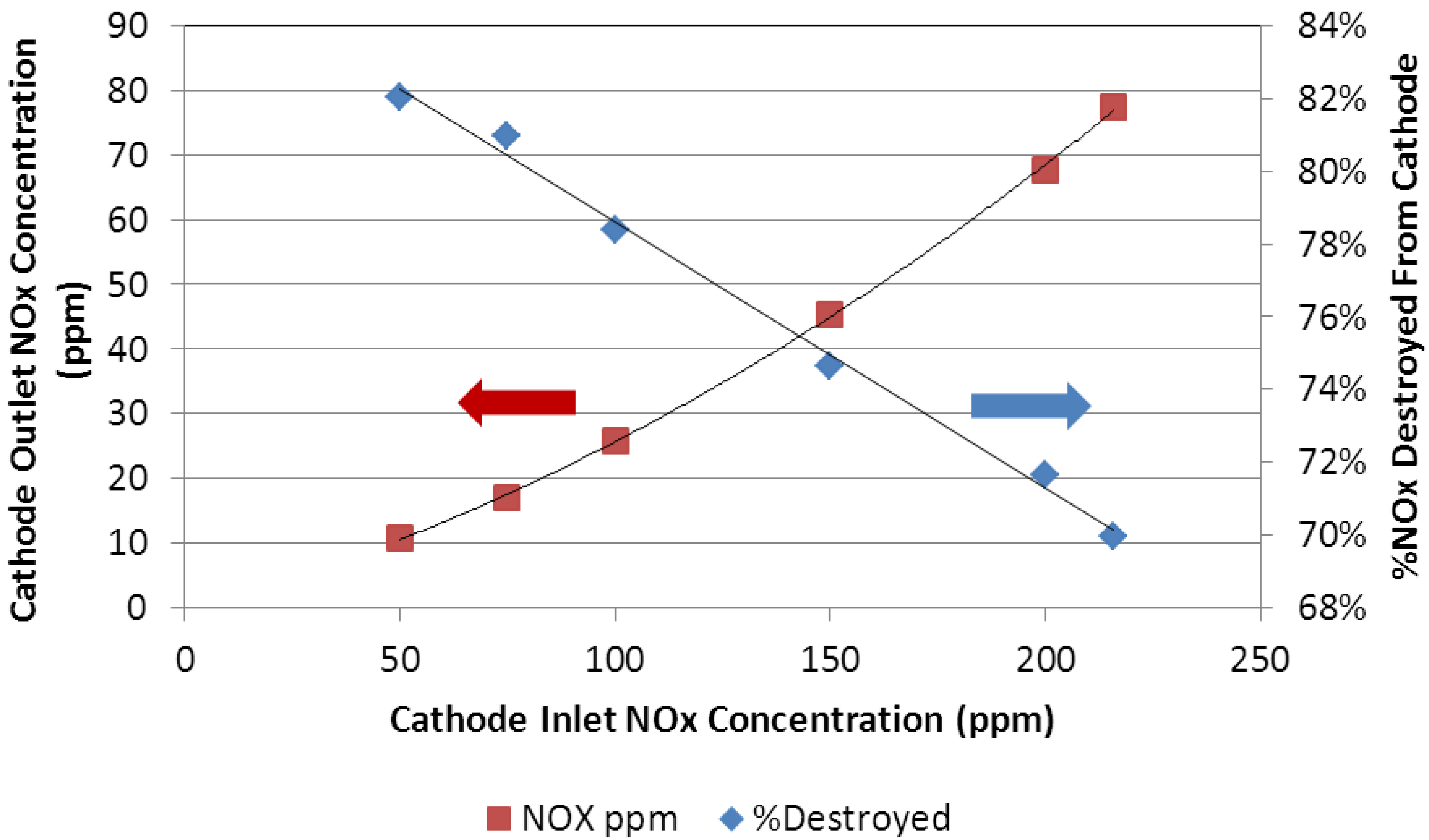
ECM NO_x Removal Mechanism

- 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

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

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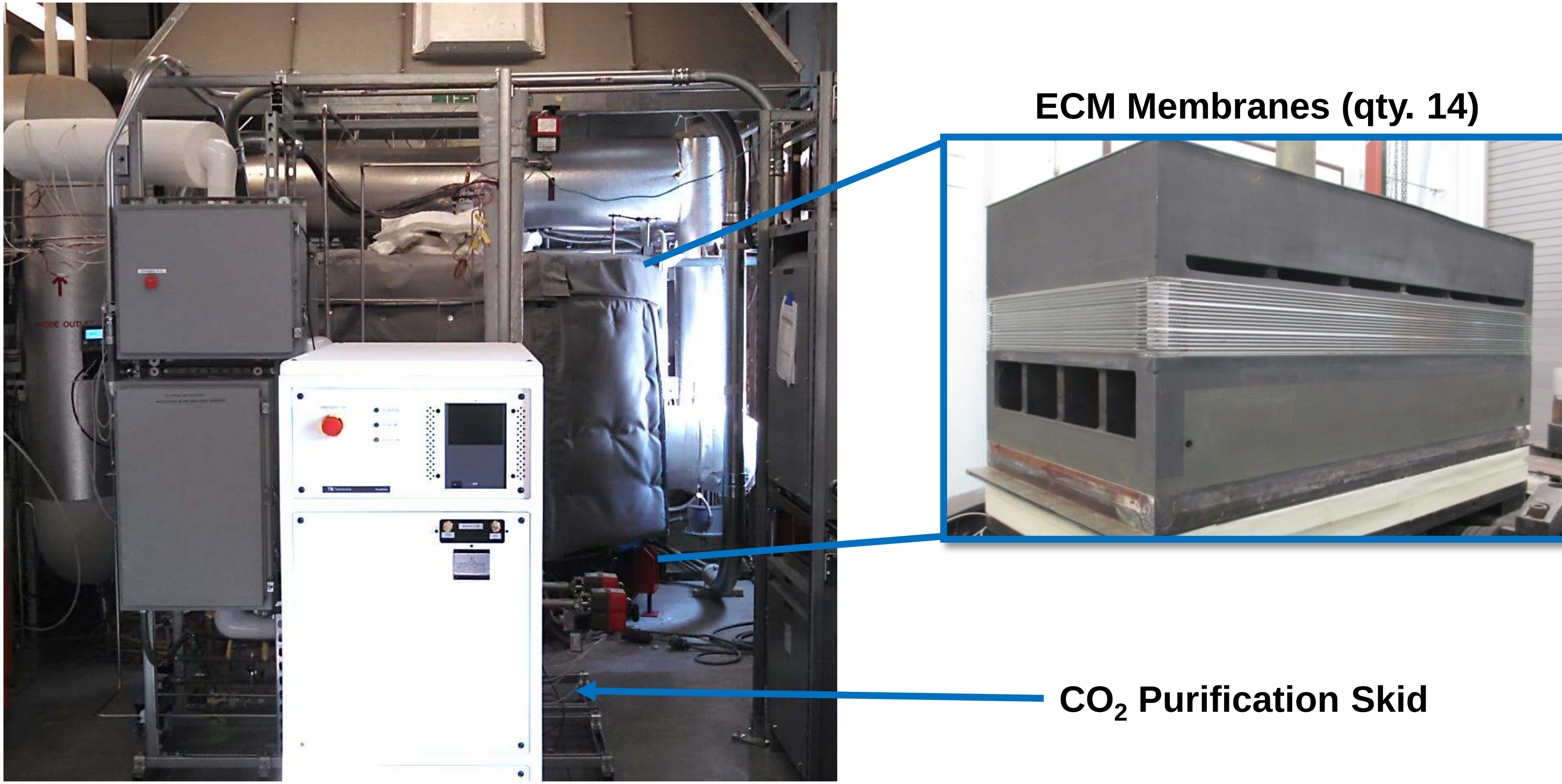
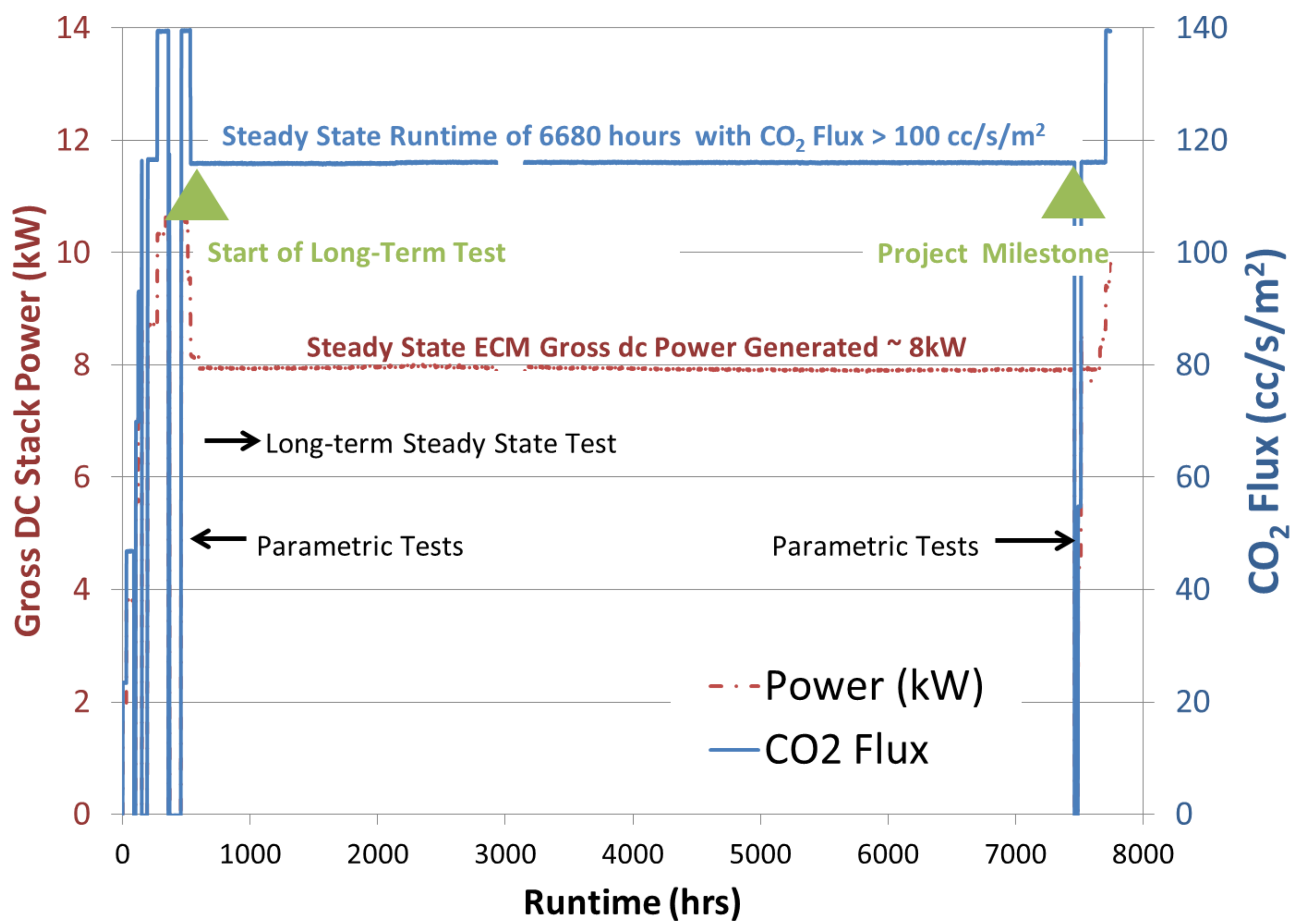
Bench-Scale Demonstration System



CEPACS Demonstration System:

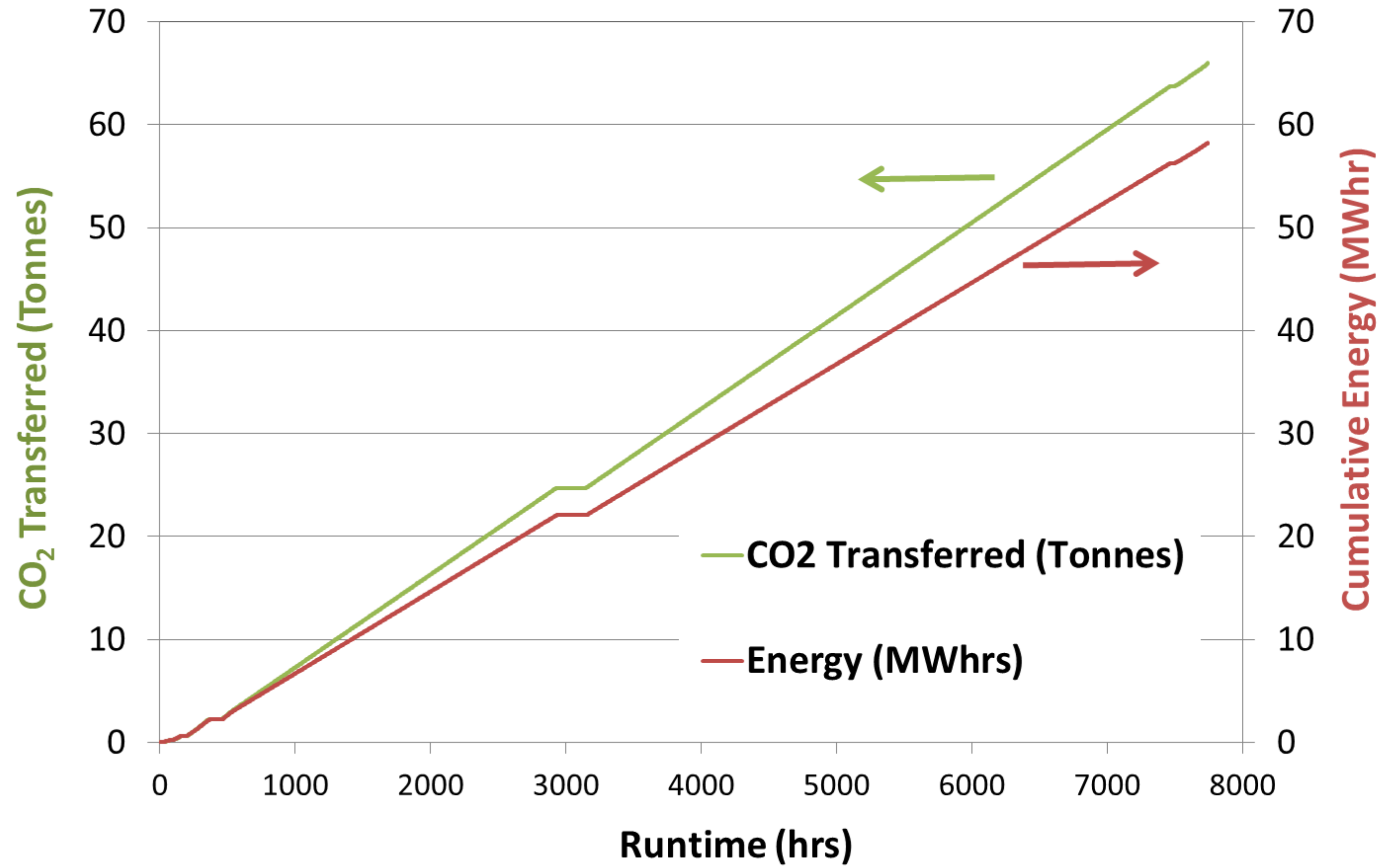
- Designed for 100 tons/year liquid CO_2 product
- Capable of >10 kW peak power production

Bench-Scale Demonstration Results



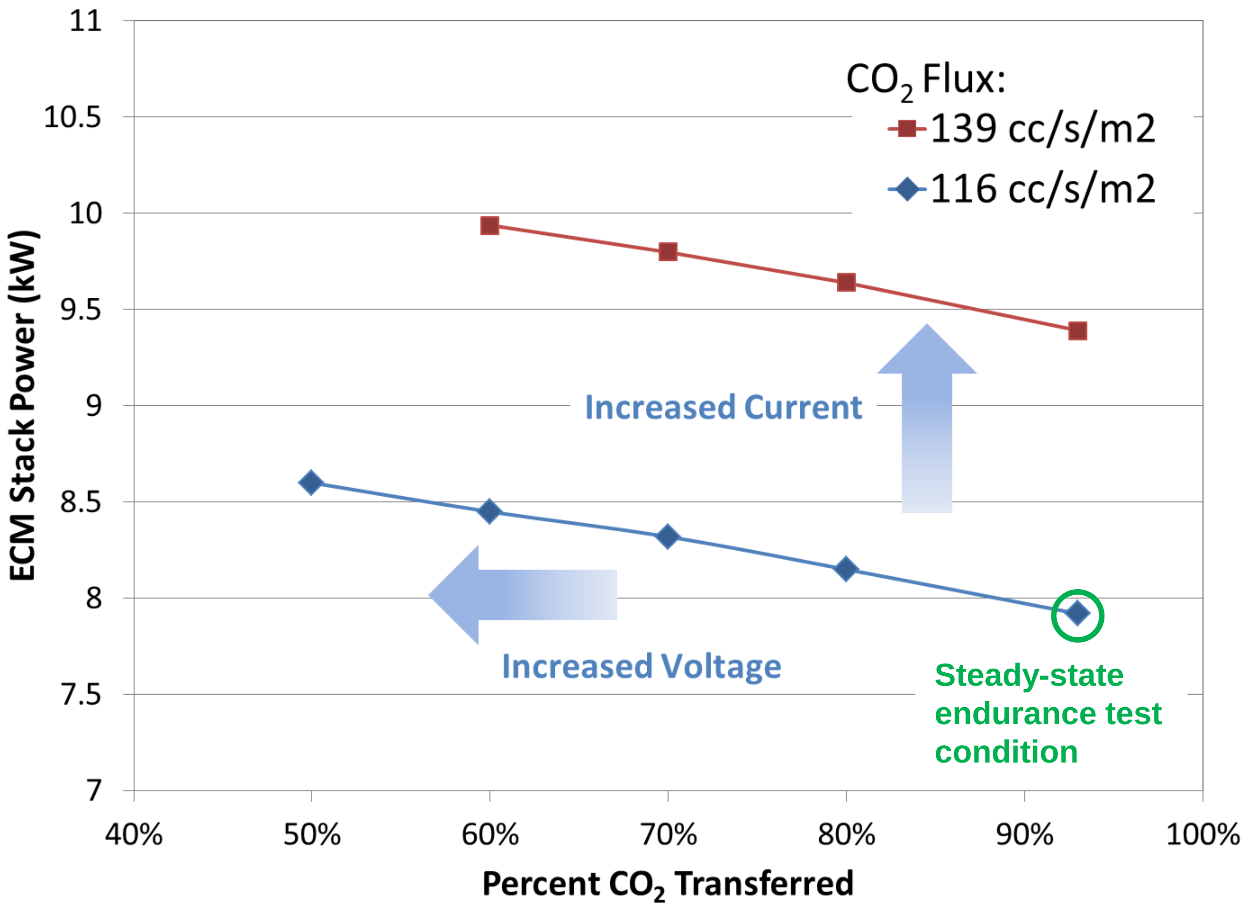
Bench-scale CEPACS test results verified CO_2 flux greater than 15% over targeted milestone value (>100 cc/s/m^2) and stable operation for >9 months

Bench-Scale Demonstration Results



Bench-scale ECM separated 66 Tonnes CO_2 from simulated PC plant flue gas, generating 58 gross megawatt-hours of electricity.

Bench-Scale Demonstration Results: Parametric Testing

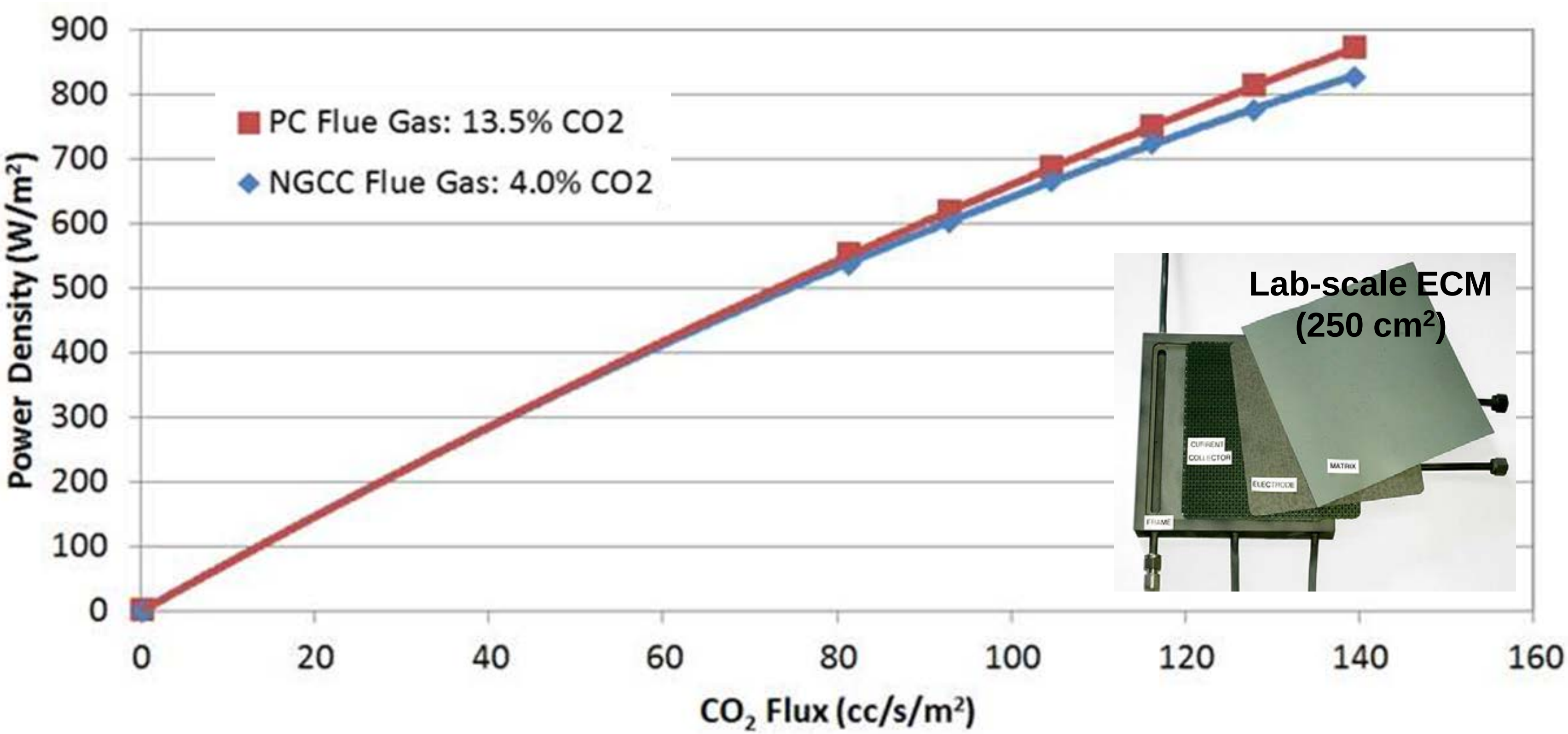


- ECM is capable of operating at higher CO_2 flux (>20% improvement) than baseline conditions, with proportional increase in power generation
- ECM power output (and efficiency) increases slightly as CO_2 capture % decreases

Other Applications

ECM Performance: Effect of Flue Gas Composition

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



- High cell power densities at high CO_2 flux is observed in ECM tests
- 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

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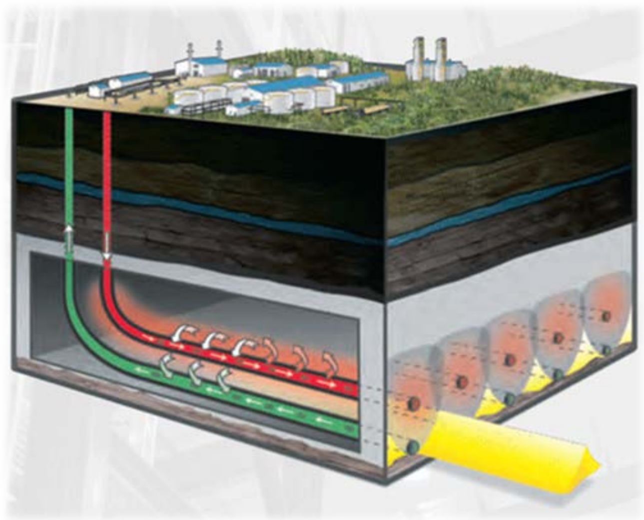
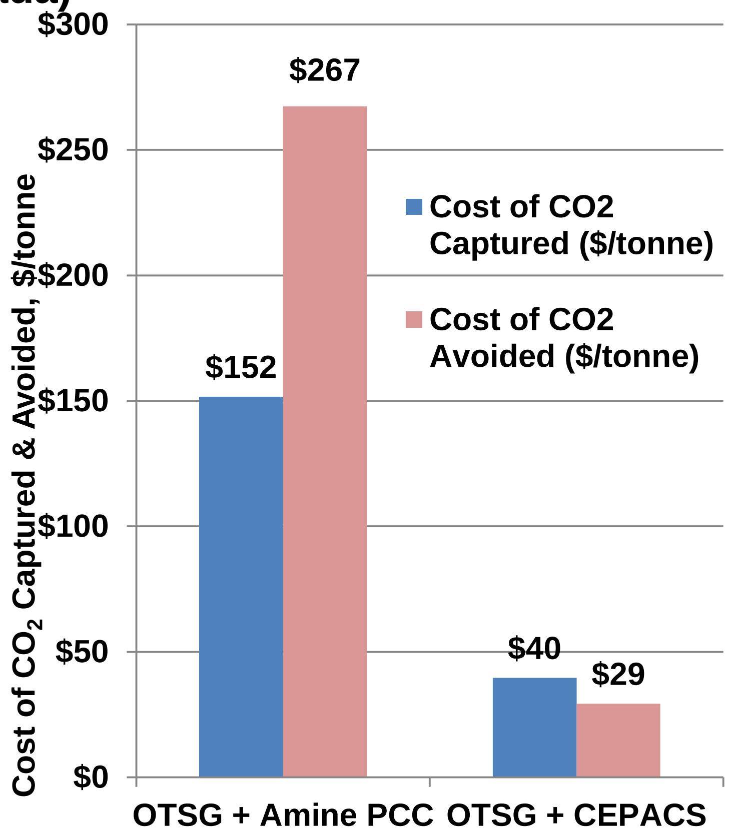
Case Study: ECM for CO_2 Capture from SAGD Bitumen Extraction

Jacobs Consultancy developed an independent analysis* of a CEPACS 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)





CEPACS 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

Accomplishments and Summary

- The Technical and Economic Feasibility Study (T&EFS) of a CEPACS system to separate 90% of CO_2 from the flue gas of a Reference Plant (550 MW PC) has verified:
  - ECM increases output and efficiency compared to base plant without CO_2 capture
  - Incremental cost of electricity (COE) of 35% and cost of CO_2 captured of $38/tonne CO_2 (2011 USD)
  - Excess water available for export
- ECM laboratory tests verified:
  - ECM is stable in the presence of S, Se, Cl, and Hg levels expected from a wet-FGD polisher
  - Capability to destroy 70-80% of NO_x from flue gases
  - Capability to separate CO_2 from flue gasses with low (<4%) CO_2 concentration

Fuel Cell Manufacturing Facility, Torrington, CT

- The Technology Gap analysis indicated that available commercial equipment can be used in CEPACS system with no R&D needed for BOP
- ECM is suitable for a wide range of carbon capture applications: Enhanced oil recovery, SAGD Oil Sands, coal and natural gas power plants, and industrial sites (cement factory & refineries)
- Completed steady state bench-scale tests of a bench-scale ECM stack achieving a stable CO_2 separation flux greater than the targeted 100 cc/s/m^2 while generating ~ 8 kW of gross power

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Acknowledgements

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