# Systems Analysis of Fuel Cell Plant Configurations

NATIONAL ENERGY TECHNOLOGY LABORATORY

Gregory A. Hackett, Ph.D.

Systems Engineering and Analysis (SEA)

June 12, 2017

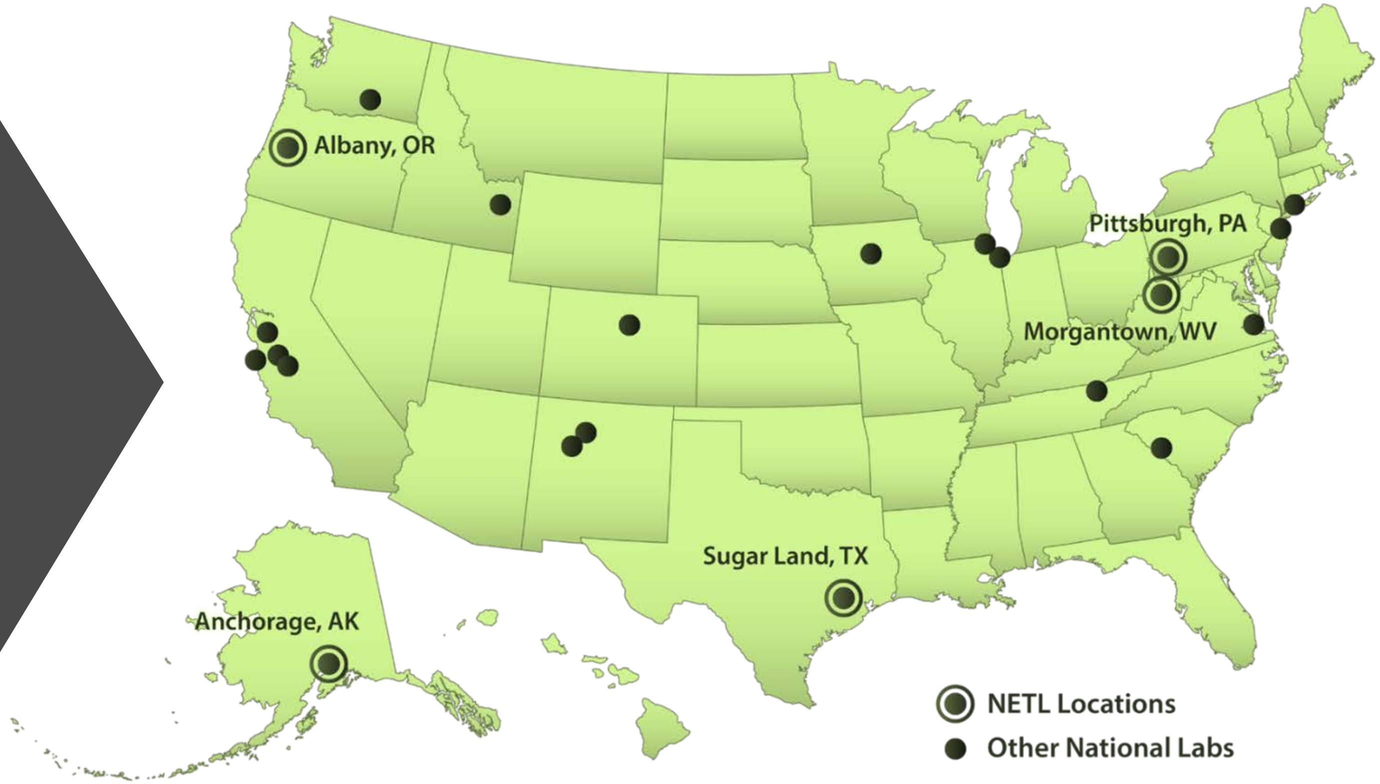
18TH Annual SOFC Project Review Meeting

Solutions for Today | Options for Tomorrow

U.S. DEPARTMENT OF ENERGY

# Outline

- SEA Primary Functions and Objectives
- SOFC Technology Development Plan
- Distributed Generation Market Analysis Update
- Pathway Studies
  - NETL Systems Model Enhancement



# SEA Primary Functions and Objectives

- **Assess Technology Cost and Performance**
  - Compare advanced technologies with current state-of-the-art (SOTA) and research and development (R&D) goals
    - Baseline studies* (current SOTA) – updated regularly
    - Screening studies for novel technologies
    - Technology pathway studies (e.g. IGFC, NGFC, IGCC, post-combustion CC)
  - Identify integration, performance, and cost requirements as appropriate for advanced technology components
  - Unbiased assessments of technology options
- **Assist NETL Science & Technology Strategic Plans & Programs**
  - Funding Opportunity Announcement preparation
  - Proposal reviews
  - Critiques of external system studies

# SEA Primary Functions and Objectives

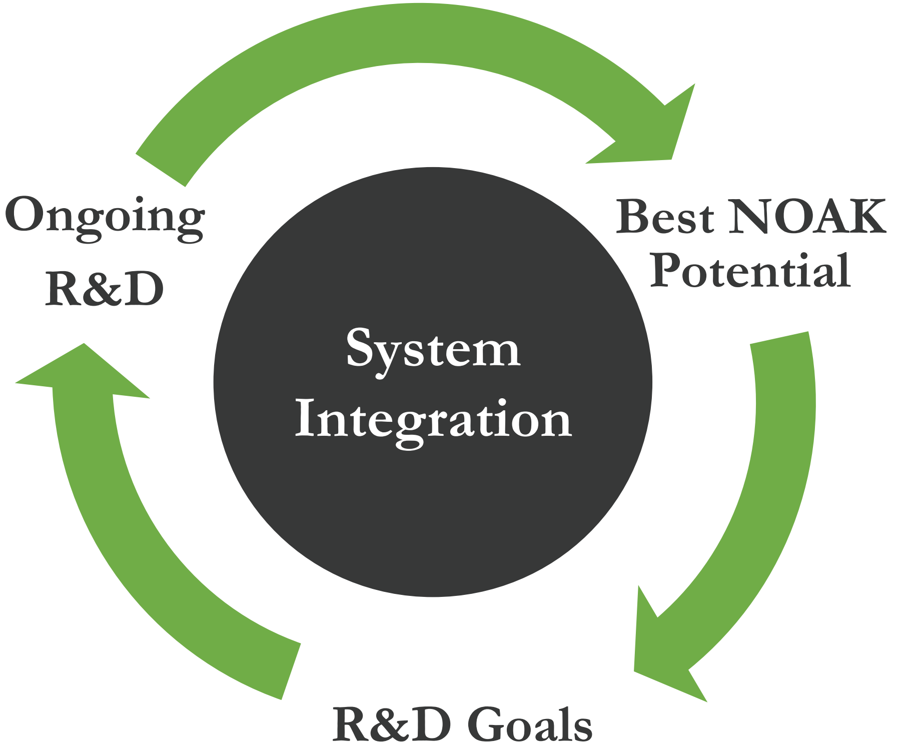
NATIONAL ENERGY TECHNOLOGY LABORATORY

**1**

Assess technology based on current data from ongoing R&D

**2**

Based on initial assessment, estimate best possible NOAK performance potential




**3**

Compare best NOAK performance to R&D goal; determine if/how any gaps can be closed

**4**

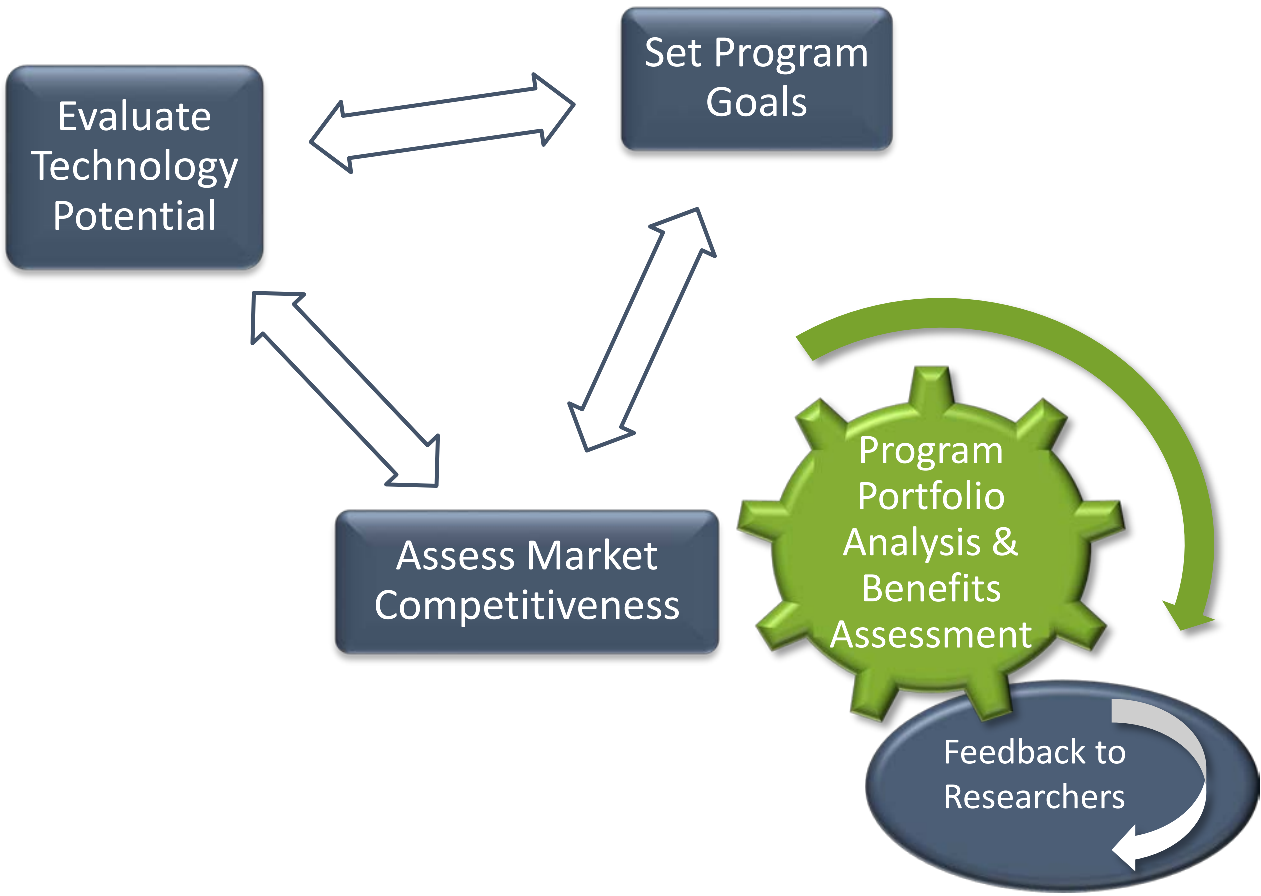
Provide feedback to researchers

# SEA and SOFC Program R&D at NETL

- **How do SEA analyses directly impact SOFC research at NETL?**

- **Systems Engineering and Analysis**
  - Informs Program of technology potential
  - Assists in establishing programmatic goals
  - Assess markets

- **Research and Development Efforts**
  - Directly addresses programmatic goals
  - Direct interaction with SOFC developers
  - Multi-disciplinary, collaborative effort



# SOFC Technology Development Plan

NATIONAL ENERGY TECHNOLOGY LABORATORY

## CELL DEVELOPMENT (TRL 2-5)

*R&D on individual cell components*

**Challenges**
- Increase power density
- Lower degradation
- Reduce costs

**Approach**
- Innovative materials
- Increase cell area
- Automation

## MODULE and BOP (TRL 2-5)

*R&D on stack components, modules, and BOP*

**Challenges**
- Thermal gradients
- Flow maldistribution
- Lower cost

**Approach**
- Modeling
- Robust/low cost materials
- In-stack fuel reformation

## INNOVATIVE CONCEPTS (TRL 3-7)

*R&D on second generation cell and stack technology*

**Challenges**
- Reduce degradation
- Improve reliability
- Lower cost

**Approach**
- Modeling
- Compact design
- Advanced manufacturing

## SYSTEMS INTEGRATION (TRL 6-8)

*RD&D leading to entry-into-service power systems*

**Challenges**
- Integration of components
- Complexity
- Operating strategy

**Approach**
- Systems analysis
- Progressively larger system tests
- Multiple demonstrations

* State-of-the-art
** Proof-of-concept
*** First-of-a-kind
**** N-th-of-a-kind

SOA* 50 kWe POC**
Test complete
Integrated system
TRL 6

SOA 200 kWe POC
Test complete
Integrated system
Pressurized
TRL 6

2nd Generation
5 kWe stack test
TRL 5

SOA 400 kWe
Integrated system
TRL 7

SOA 500 kWe
Integrated system
TRL 7

2nd Generation
25-50 kWe POC
Integrated system
TRL 6

SOA MWe-class
Demo
FOAK***
TRL 8

10 MWe Demo(s)
IGFC/NGFC slipstream
CCS
TRL 7

Commercial DG Systems
NOAK****
MWe-class
Natural gas
TRL 9

2nd Generation
500 kWe
Integrated system
TRL 7

Commercial DG Systems
MWe-class
Natural gas
TRL 9

50 MWe Utility-scale Demo(s)
FOAK
IGFC/NGFC
CCS
TRL 8

### MWe-Class Integrated DG System

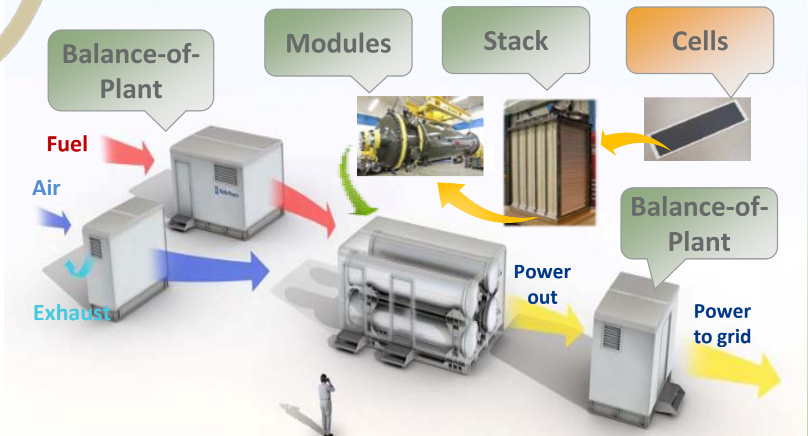



*Photo courtesy of LG Fuel Cell Systems*

# SOFC Major Development Targets

Distributed Generation (≈250 kW-1 MW) and Utility-Scale (550 MW)

- **Distributed Generation (DG)**
  - Need to explore the DG market potential of SOFC
  - An update to a previous market study is underway

- **Utility-Scale SOFC Plants (IGFC/NGFC)**
  - Establish n$^{TH}$-of-a-kind performance and cost using experimental data from state-of-the-art SOFC and defining "advanced" SOFC performance for system models
  - Sensitivity studies to determine and prioritize performance and cost parameters
  - Pathway studies (previously released in 2014/15) will be updated

# Distributed Generation Market Study Update

# Distributed Generation Market Study

Background

- **The previous study[*] explored the DG market potential of SOFC**
  - DG market opportunity: electric power (250 kWe to MWe class units)
    - SOFC DG electric power application
      - Provides > 20-percentage-point gain in efficiency
      - Results in significant $CO_2$ emission reduction
  - Path charted to commercial, cost-competitive SOFC DG product
    - Consistent with technology development plan
    - ~ 25 MWe installed capacity to achieve competitive cost
  - Projected learning to achieve competitive cost is consistent with similar technology commercialization experience
  - Higher natural gas price: reduces time to commercialization
  - SOFC DG applications provide path to utility scale plants with >98% carbon capture with efficiencies > 60% HHV

** - NETL, Assessment of the Distributed Generation Market Potential for Solid Oxide Fuel Cells (September 2013)*

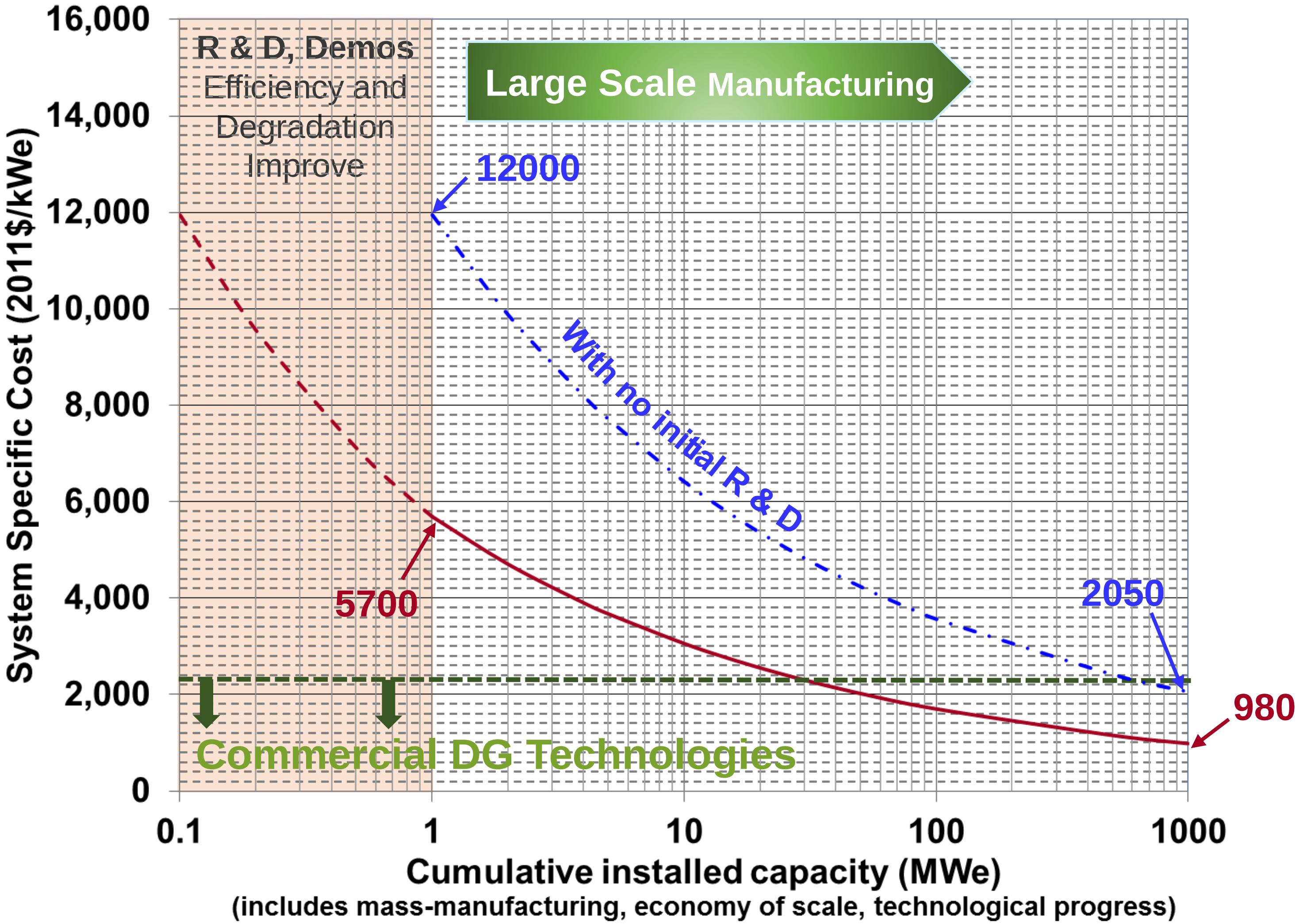
# Distributed Generation Market Study

## Objective

- **The objective of the present study is to update the previous analysis**
  - Update DG Market Projections
    - Identify appropriate market segment for SOFC
    - Integrate Department of Defense (DoD) opportunity analysis
  - Better represent competing technologies
    - Include renewable technologies – solar photovoltaics (PV), geothermal, wind, etc.
    - Update competing technologies costs data as available
    - Update subsidies/incentives
  - Update reference DG - SOFC system costs
    - Potentially include a reference pressurized system
  - Update learning curve analysis
    - Include learning curves for competing technologies
    - Installed capacity to achieve competitive cost
  - Update capacity/learning projected to achieve competitive cost

# SOFC Learning Curve Analysis Update

Specific Cost versus Installed Capacity

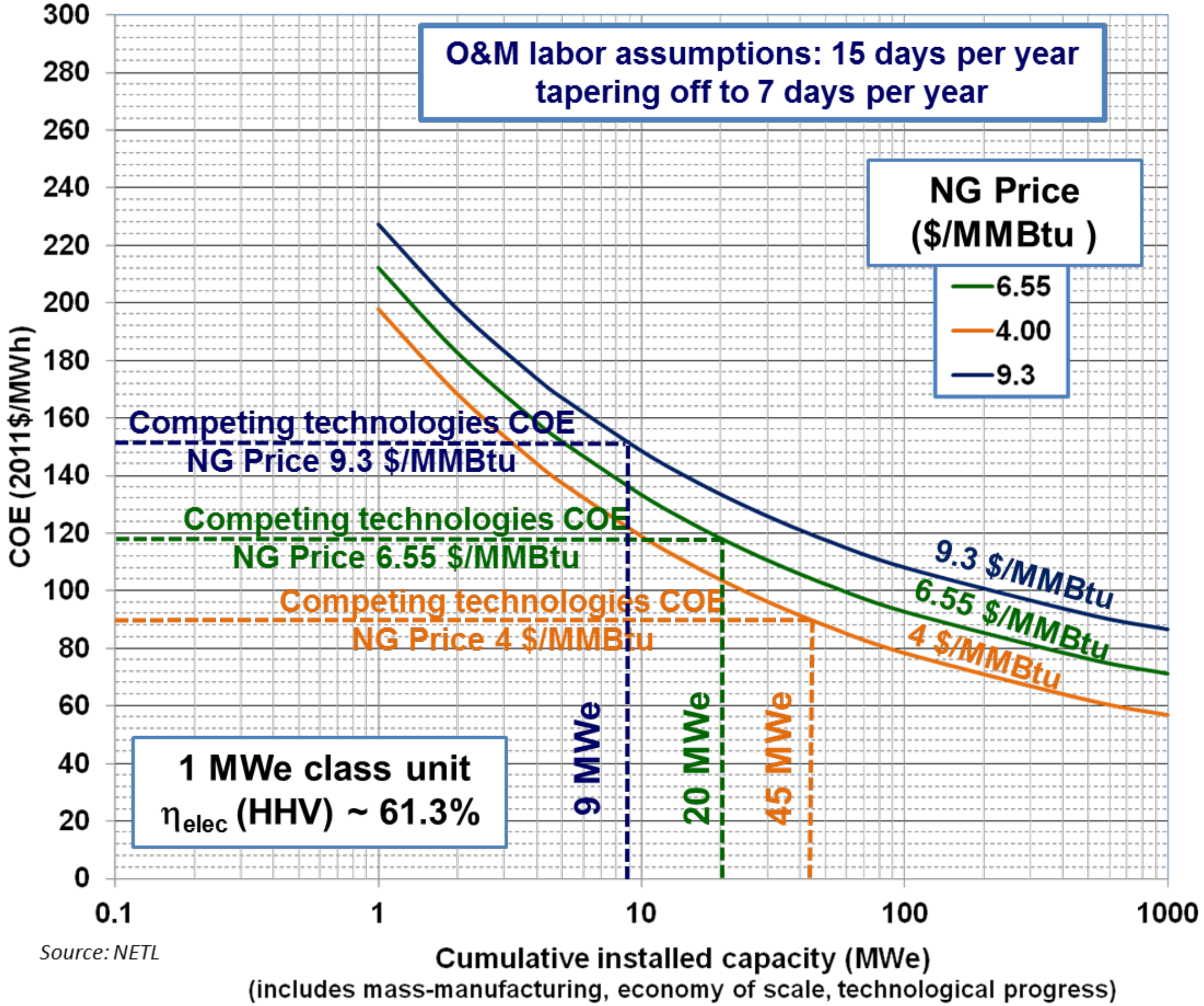



- Update learning curve to be consistent with the capital vs. installed capacity plot and the SOFC roadmap
- Include learning curve for competing commercial DG technologies

*Source: NETL*

# SOFC Learning Curve Analysis Update

COE versus Installed Capacity




*Source: NETL*

- Update the sensitivity of natural gas prices on cost-of-electricity (COE)
- As natural gas prices decrease, more installed DG SOFC capacity needed to be cost competitive

# NETL SOFC System Model Enhancement

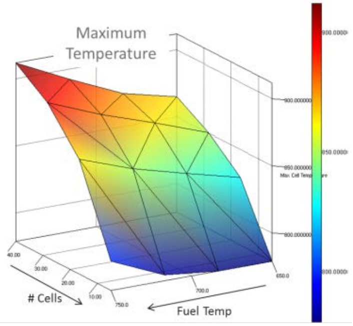
## Incorporation of PNNL SOFC-MP Model

# Background

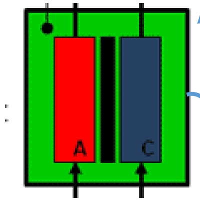
## NETL/PNNL Collaboration to Complete Scaling Process

**Need design and engineering at several scales to facilitate wide-scale SOFC commercialization**

**Link NETL and PNNL models at different scales to inform system level and life cycle analyses**



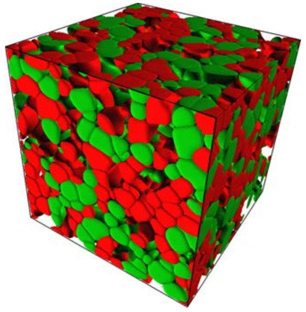

Response Surface Analysis

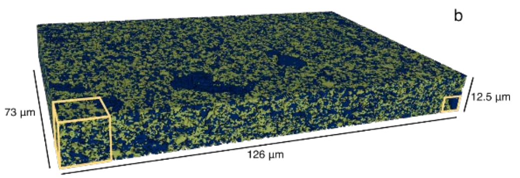



Reduced Order Model (ROM)

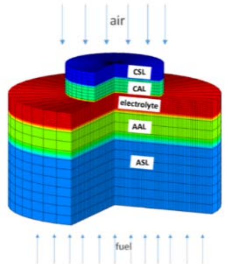
Stack Details

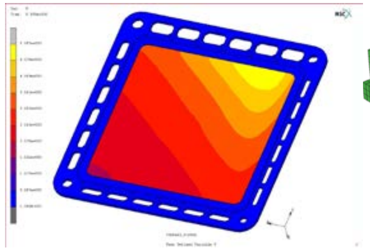
Increasing Scale



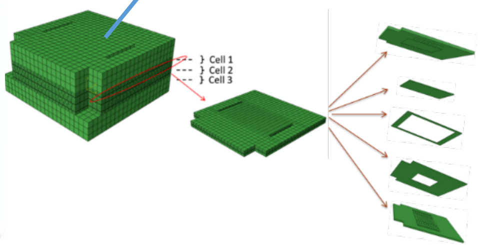



Electrode Microstructure

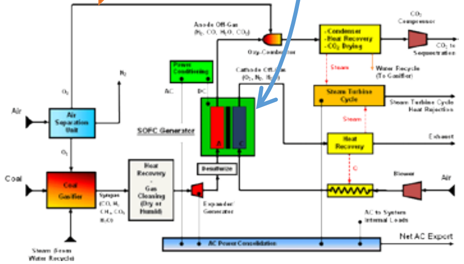


Single Cell




Multi-Cell Stack




IGFC System Model

*NETL* *NETL*

*PNNL*

# Pathway Studies

NATIONAL ENERGY TECHNOLOGY LABORATORY

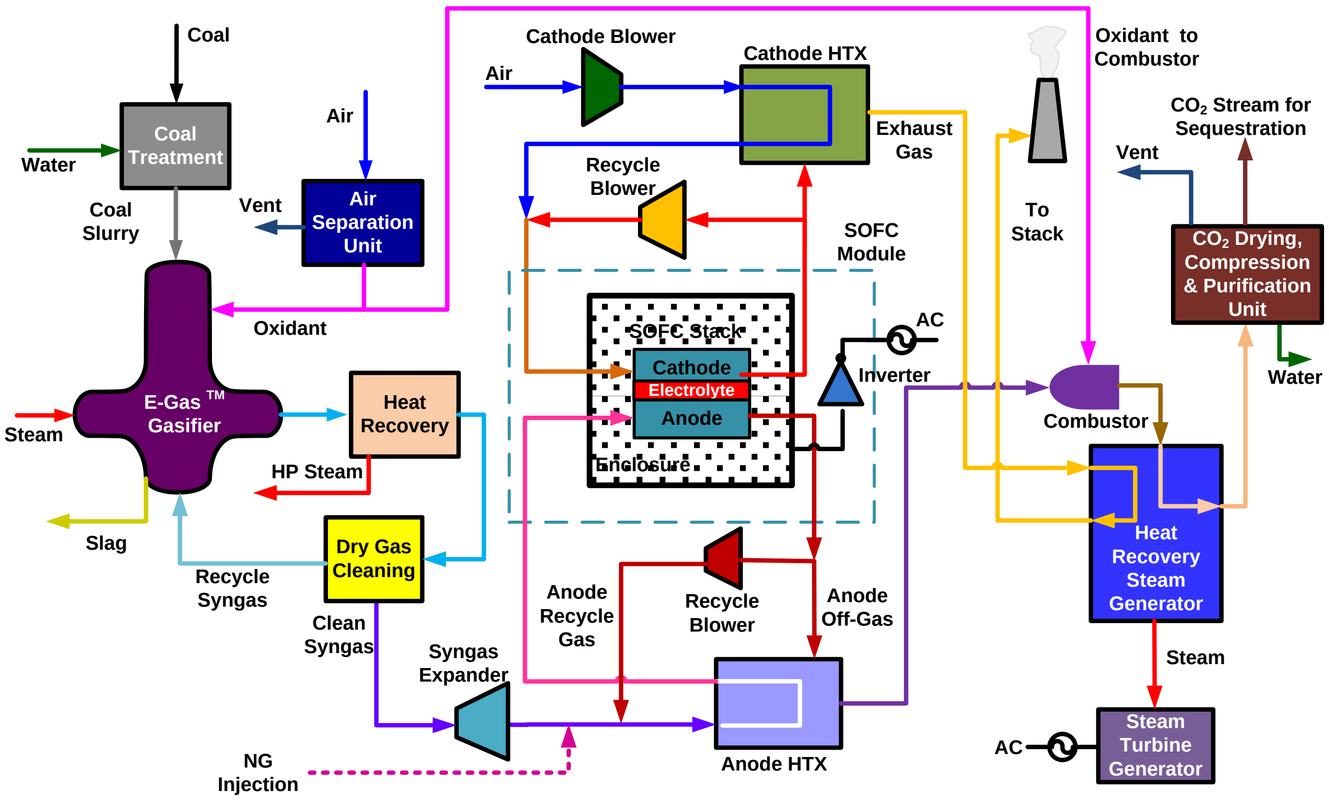
- **Pathway studies provide information on the significance that incremental improvements have toward reaching a technology's full performance/cost potential**

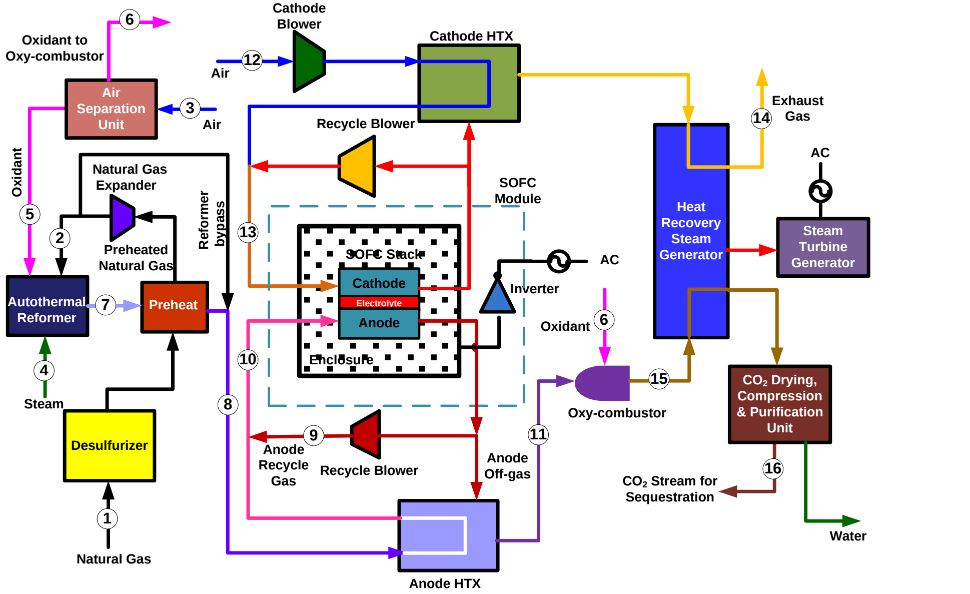
- **Cost and performance information at each step**
  - Evaluates several operating conditions/plant configurations and improvements to minimize COE/maximize efficiency
  - Ability to include performance degradation models developed at micro-scale
  - Includes program goals and targets
  - Provides apples-to-apples comparison to other technologies
  - Demonstrates the significance R&D has on technology commercialization

# Pathway Studies

## Utility-Scale IGFC/NGFC Power Plants

- Pathway studies evaluate performance and cost of utility-scale (≈550 MWe) SOFC-based power plants




*NETL, Techno-Economic Analysis of Integrated Gasification Fuel Cell Systems, November 2014, DOE/NETL-341/112613*

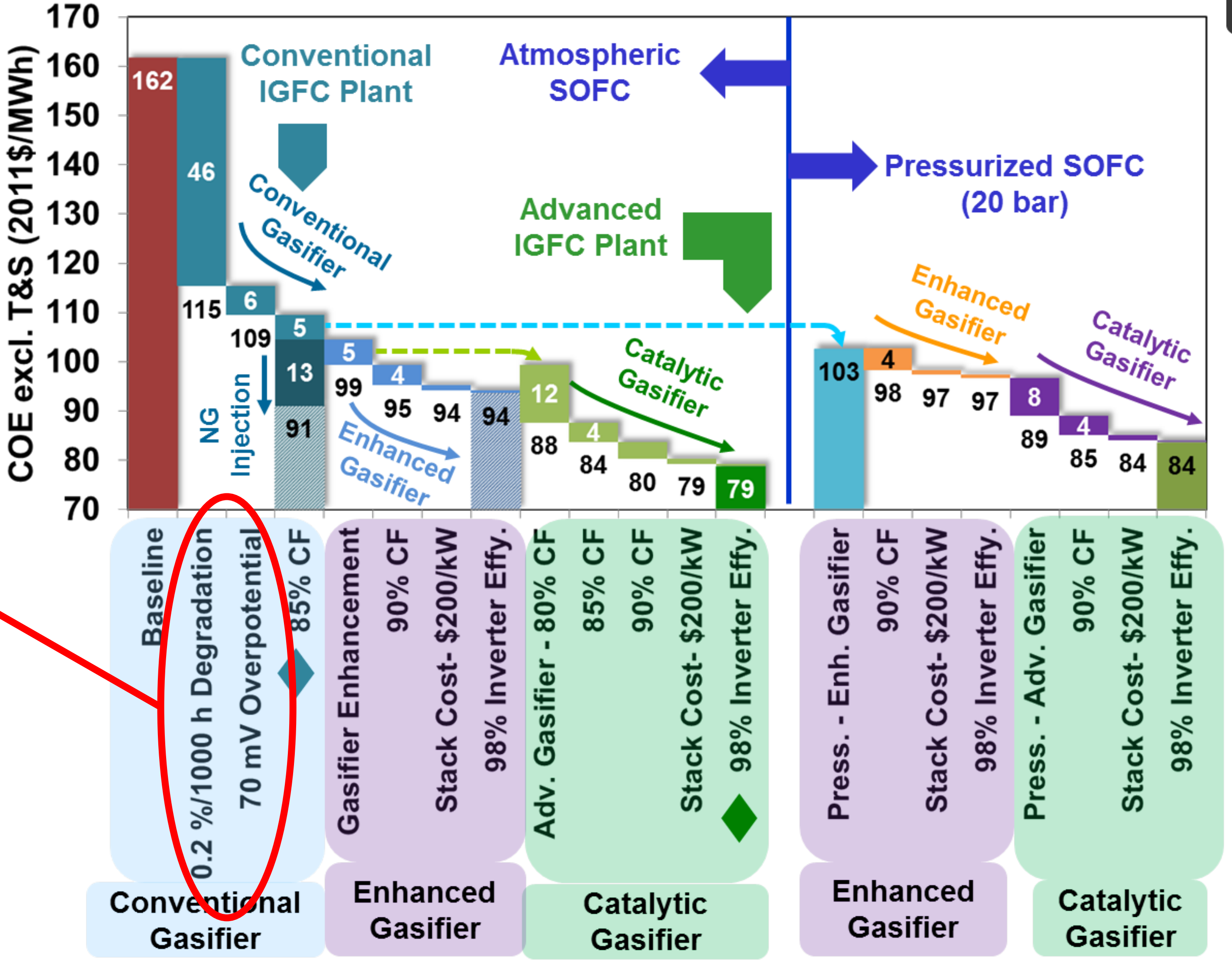
*NETL, Techno-Economic Analysis of Natural Gas Fuel Cell Plant Configurations, April 2015, DOE/NETL-2015/04082015*

# Pathway Studies

Cost of Electricity

**REDUCE stack degradation**

**REDUCE cell overpotential**




All cases include 90% $CO_2$ capture

| Baseline | |
|---|---|
| Overpotential [mV] | 140 |
| Fuel Utilization [%] | 90 |
| Degrad. [%/1000 h] | 1.5 |
| Inverter Effy. [%] | 97 |
| Stack Cost [$/kW] | 225 |
| CF [%] | 80 |

Source: NETL

# NETL SOFC System Model Enhancement

Objective

- **Improvement of the accuracy and capability of NETL's ASPEN-based SOFC system analysis**
  - To produce a variety of optimization and what-if studies to guide the SOFC R&D Program
- **NETL analysis of SOFC systems is limited to what can be described as a "black box" SOFC module with the current ASPEN system model**
  - Two reactors (cathode/anode) with heat and oxygen transfer
  - Specified overpotential estimates
  - Limited potential to optimize on system level

# NETL SOFC System Model Enhancement

Objective

- **Solution – Integrate the PNNL SOFC-MP model into NETL's system model as a reduced-order model (ROM)**
  - Increase the accuracy of SOTA SOFC analysis
  - Reduce computational time and complexity versus full model
  - Allow for additional optimization studies (COE, etc.)
  - Allow for the ease of incorporation of other models
    - Such as degradation models, etc.
  - Facilitate development of a high fidelity SOFC tool for system analysis
    - An NETL/DOE/PNNL vision
    - SOFC industry team use

# NETL SOFC System Model Enhancement

Description

NATIONAL ENERGY TECHNOLOGY LABORATORY

- **Stack Model**
  - Planar, adiabatic stack is used for input into ROM process
  - Stack is modeled using PNNL's SOFC-MP software
    - Solves for gas species, temperature, and current density
  - 550 $cm^2$ active area anode-supported cell with metal interconnects
  - Counter-flow configuration
  - Assumes water-gas shift reaction is in equilibrium
  - Uses a first-order kinetic expression for the slower on-cell steam reforming of methane with a Ni-YSZ anode

# NETL SOFC System Model Enhancement

Description

NATIONAL ENERGY TECHNOLOGY LABORATORY

- **Electrochemical Model**
  - Current-voltage relationship for the cell is defined by a user-defined function that returns a voltage based on the local temperature, species concentrations, and current density at each location of the cell's active area
  - The coefficients used in the polarization equations provide an I-V response representative of high performing SOTA planar cells
  - Provides 0.8 V at 400 mA/cm² for a wet $H_2$ fuel, with 75% $U_F$, and 12.5% $U_A$

# NETL SOFC System Model Enhancement

ROM Parameters

| Variable | Range | Description |
| --- | --- | --- |
| Average Current Density | 2000-6000 A/m² | Cell operating current |
| Internal Reforming | 0-100% | The degree of external reforming |
| Oxidant Recirculation Fraction | 0-80% | Fraction of cathode exhaust recirculated |
| Oxygen-to-Carbon Ratio | 1.5-3.0 | Defines the fuel exhaust recirculation needed to achieve the desired O/C ratio at stack inlet |
| System Fuel Utilization | 40-95% | Overall fuel utilization |
| System Oxidant Utilization | 12.5-83.3% | Overall oxidant utilization |
| Fuel Inlet Temperature | 550-800°C | Fuel temperature at stack inlet |
| Air Inlet Temperature | 550-800°C | Oxidant temperature at stack inlet |

# NETL SOFC System Model Enhancement

Test Case Results

| | Input/Output | Test Case 1 | Test Case 2 |
|---|---|---|---|
| Average Current Density | Input | 4000 A/m² | 4000 A/m² |
| Internal Reforming | Input | 60% | 60% |
| Cathode Exhaust Recirculation Fraction | Input | 50% | 50% |
| Oxygen-to-Carbon Ratio | Input | 2.6 | 2.1 |
| System Fuel Utilization | Input | 90% | 80% |
| Cell Maximum Temperature | Input Constraint | 750°C | 750°C |
| Cell ΔT | Input Constraint | 100°C | 100°C |
| Fuel Recirculation | Output | 56.0% | 44.9% |
| Stack Oxidant Utilization | Output | 27.73% | 23.04% |
| Fuel Inlet Temperature | Output | 550°C | 550°C |
| Air Inlet Temperature | Output | 627°C | 688.5°C |
| Cell Voltage | Output | 0.958 V | 0.966 V |
| NGFC System Efficiency (HHV) | Output | 56.5% | 53.9% |

# NETL SOFC System Model Enhancement

Next Steps

- **NETL was recently supplied with an improved ROM to incorporate into the system model**
  - Includes more unit ops within the ROM envelope
  - Extension to different fuel compositions (i.e. coal syngas)
- **NETL is working to identify an advanced SOFC performance electrochemical model to generate a ROM**
- **Begin generating data to update IGFC/NGFC Pathway studies (FY18)**
  - Include results from recent studies
    - Vent-gas recirculation configuration
    - Operating pressure sensitivity
    - Other incremental improvements

# Acknowledgments


| NETL | PNNL | KeyLogic/Deloitte |
| --- | --- | --- |
| Shailesh Vora | Brian Koeppel | Arun Iyengar |
| Joe Stoffa | Kevin Lai | Howard Bugg |
| Heather Quedenfeld | Kurt Recknagle | Dale Keairns |
| Travis Shultz | | Mark Woods |
| Kristin Gerdes | | Joe Pierre |



Gregory Hackett
Technical Project Monitor – Fuel Cells
Systems Engineering and Analysis, Energy Process Analysis Team
Gregory.Hackett@netl.doe.gov

# NETL SOFC Group Posters

- Multi-physics Modeling of Solid Oxide Fuel Cells with Parallel Oxygen Reduction Reaction Pathways, Tao Yang
- Density-Functional Study of the $La_2Zr_2O_7$ Low-Index Faces, Yves Mantz
- Nanostructure Degradation of LSM/YSZ Interface from the Active Layer of the SOFC Cathode Operated with Elevated Steam Content, Xueyan Song
- Noninvasive Optical Sensor Development for Real-Time Solid Oxide Fuel Cell Monitoring Applications, Youngseok Jee
- High Performance Computation of Local Electrochemistry via TPB and MIEC Pathways in SOFCs based on Morphology-Preserving Microstructural Meshes, Yu-Ting (Tim) Hsu
- Quantitative Mesoscale Analysis of SOFC Electrodes Based on 3D Reconstructions Using Xe-Plasma Focused Ion Beam (pFIB) Coupled with SEM, Rubayyat Mahbub
- Capacitance and Electrochemical Impedance Spectroscopy of a Solid Oxide Fuel Cell Interface using Phase Field Theory, Yinkai Lei
- Nano-Catalyst Infiltration by Bio-Surfactant Modification of Anode Supported SOFC Electrodes, Özcan Özmen
- Bayesian Calibration of Models of SOFC Electrode Materials, Giuseppe Brunello
- Phase Field Modeling on Initial Microstructure Effect on Grain Coarsening and Concomitant Property Degradations in SOFC Electrodes, Yinkai Lei
- Classifying Heterogeneity in SOFC Electrodes, William K. Epting
- Atomistic Modeling of Cation Diffusion in Transition Metal Perovskite $La_{1-X}Sr_XMnO_{3\pm\delta}$ for Solid Oxide Fuel Cell Cathode Applications, Yueh-Lin Lee
- Cation Segregation Analysis in SOFC – a Transmission Electron Microscope Based Study, Yang Yu
- Prediction of Performance Degradation Due to Grain Coarsening Effects in Solid Oxide Fuel Cells, Jerry Hunter Mason
- Improved Performance Stability of Solid Oxide Fuel Cells Achieved through Sr-Fe-O Infiltration of LSM/YSZ Cathode, Yueying Fan
- The Electrochemical Performance of LSM with A-site Non-Stoichiometry Under Cathodic Polarization, Jian Liu