CHANGING WHAT'S POSSIBLE

Reliable Electricity Based on ELectrochemical Systems (REBELS)

What we learned after a year and a half

Paul Albertus, Grigorii Soloveichik, John Tuttle,
Scott Litzelman, Mark Pouy

Advanced Research Projects Agency - Energy

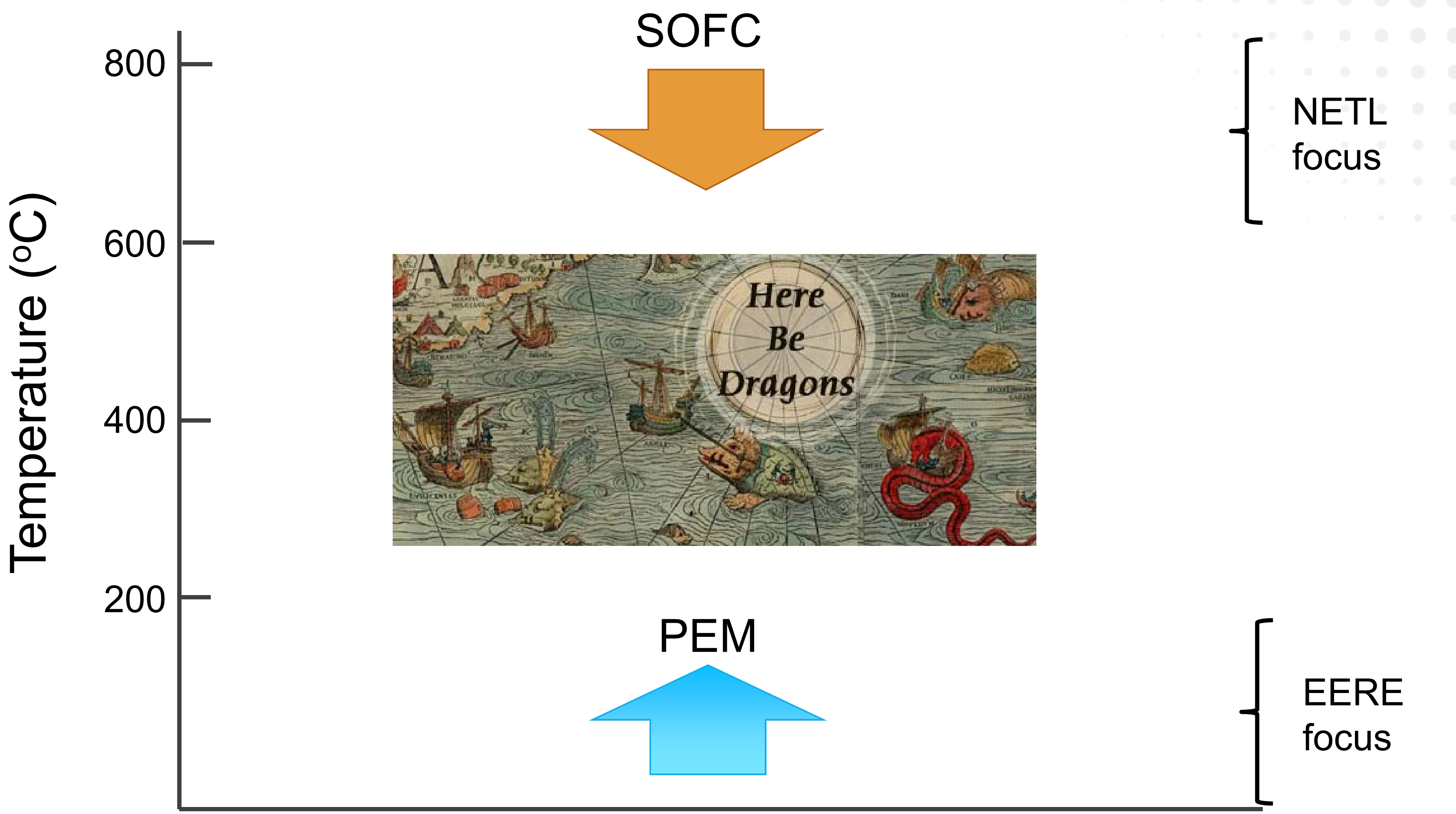
17th Annual SOFC Project Review Meeting
July 19, 2016

A tribute to John Lemmon, the REBELS founder

Electrochemical power generation will never compete economically with existing technologies such as natural gas combined cycle

New electrochemical power generation devices will **<u>revolutionize</u>** how we convert energy & be cost-competitive

A new fuel cell temperature range



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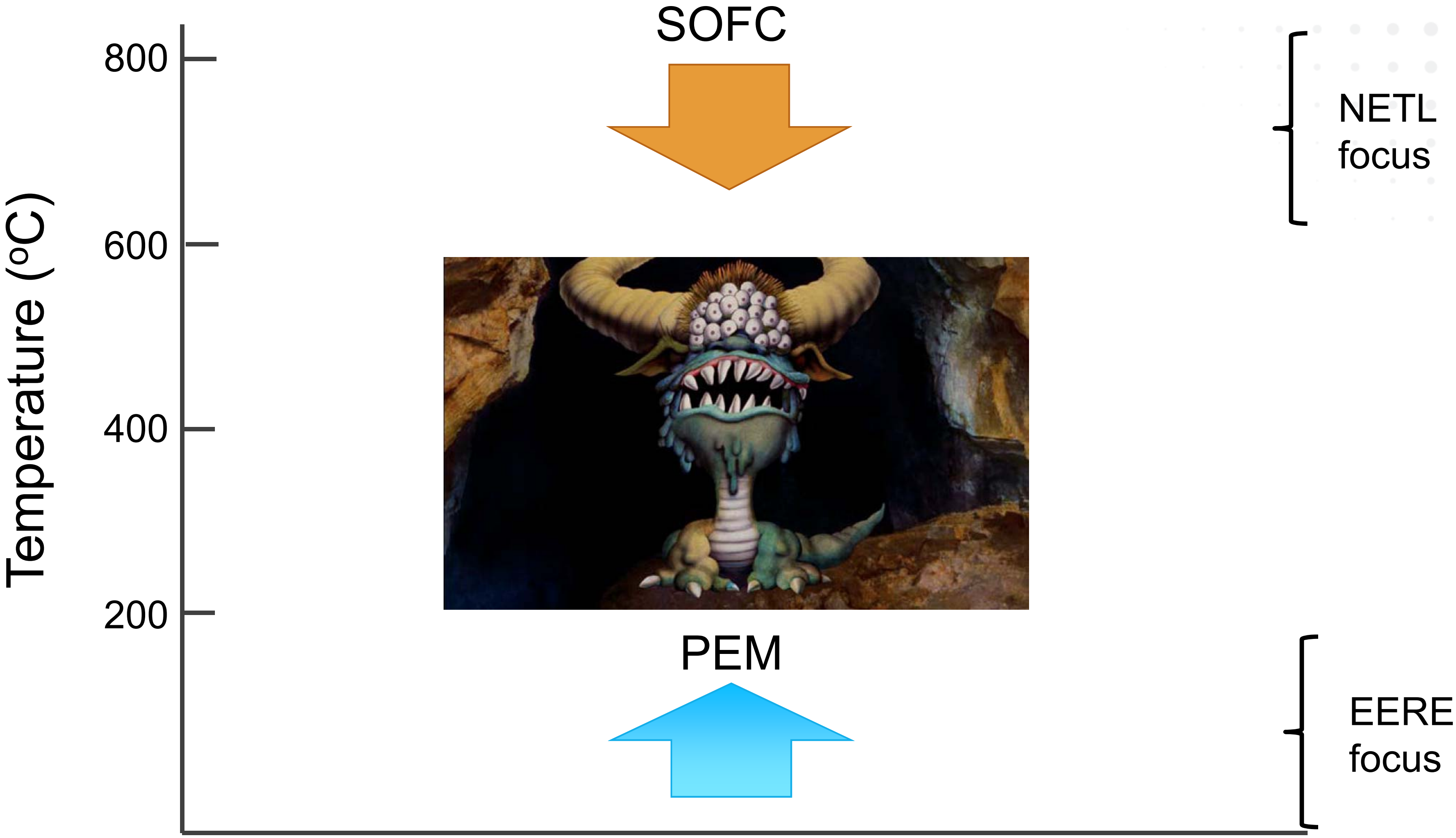


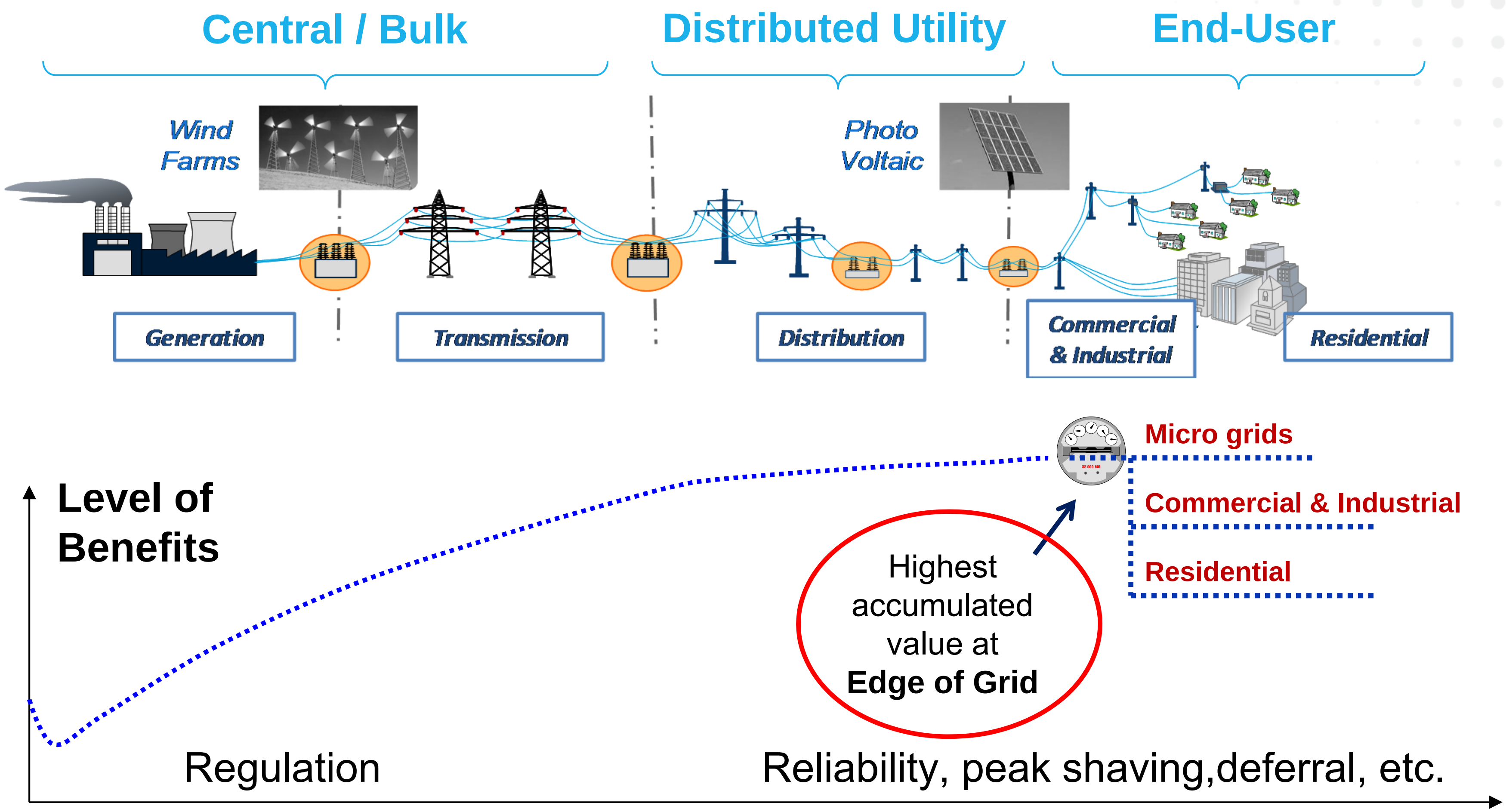
Talk outline

- Reminder of the REBELS program
  - **High-level program motivation**
  - REBELS vision and program overview

- Program categories with technical highlights
  - Category 1: Intermediate temperature fuel cells
  - Category 2: With integrated storage
  - Category 3: With integrated fuel production

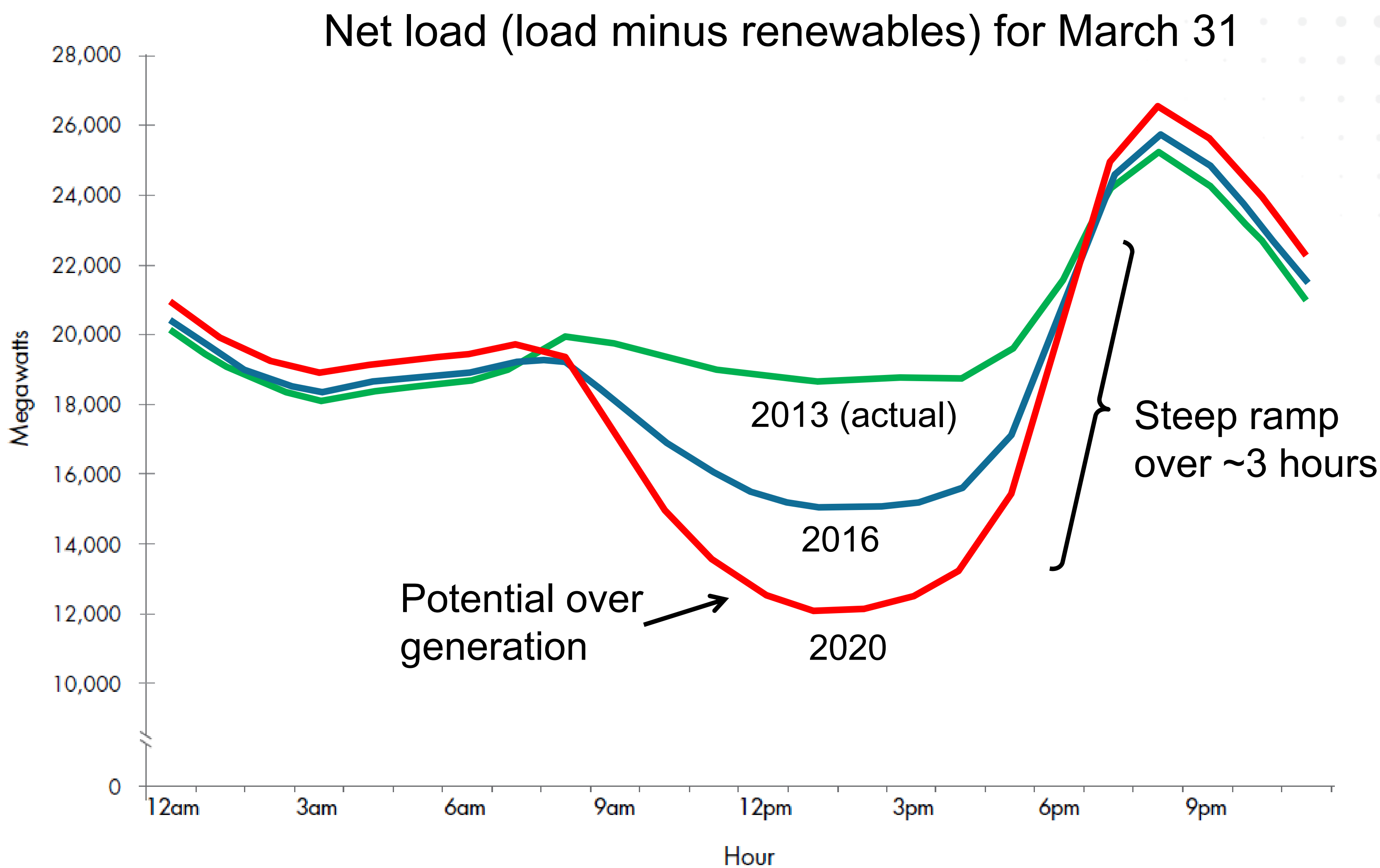
- Summary, and open questions for the REBELS program

The Value of Distributed Generation (DG)



Distributed Generation Markets – Impact of Future Fuel Cell Applications, DNV KEMA report prepared for ARPA-E (2013); Cost-Effectiveness of Distributed Generation Technologies, Itron, submitted to PG&E, 2011

The grid requires more flexible ramping



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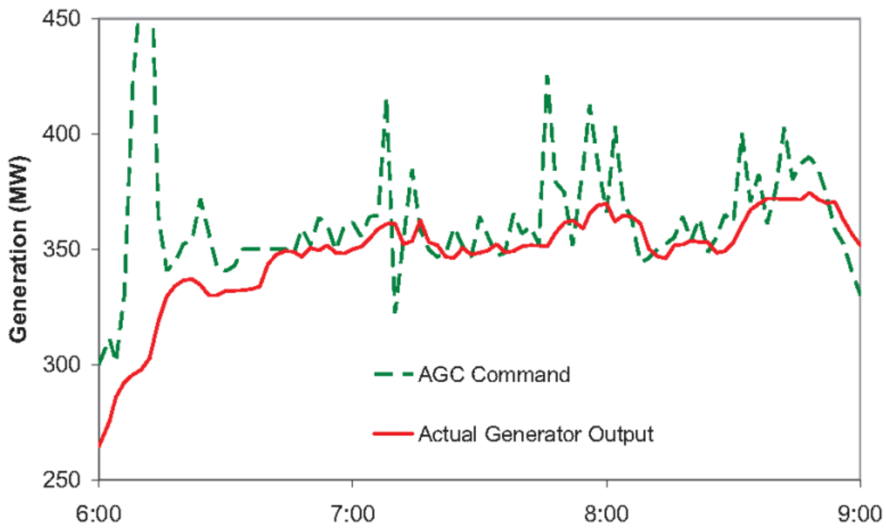
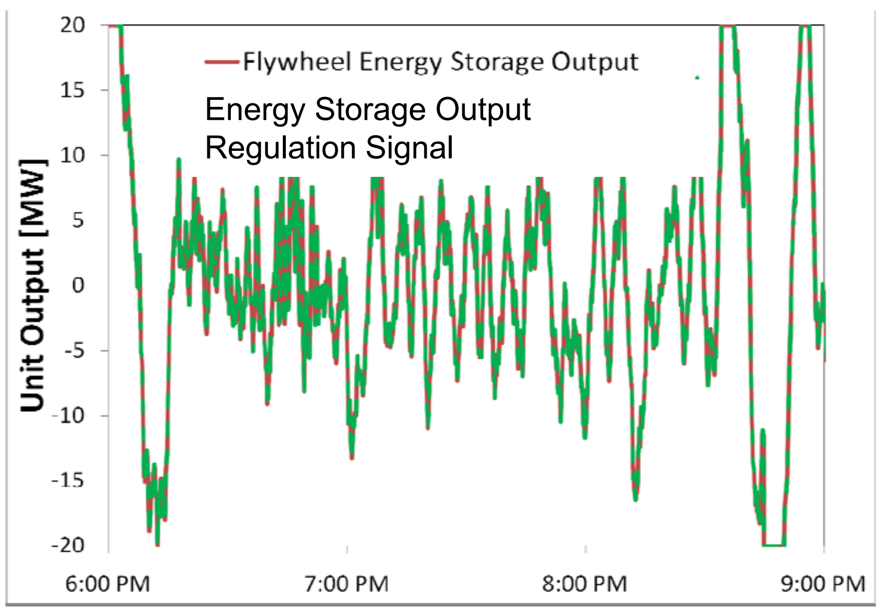
Adapted from
http://www.caiso.com/Documents/DR-EERoadmap.pdf

Battery performance in regulation



A fossil plant struggles to follow a regulation command signal



Energy storage accurately follows a regulation command signal

Electrochemistry is fast (<<1 sec) and offers value to the grid.

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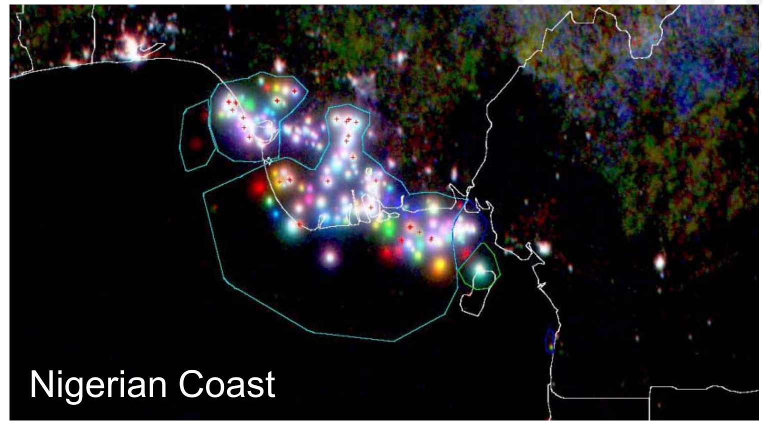
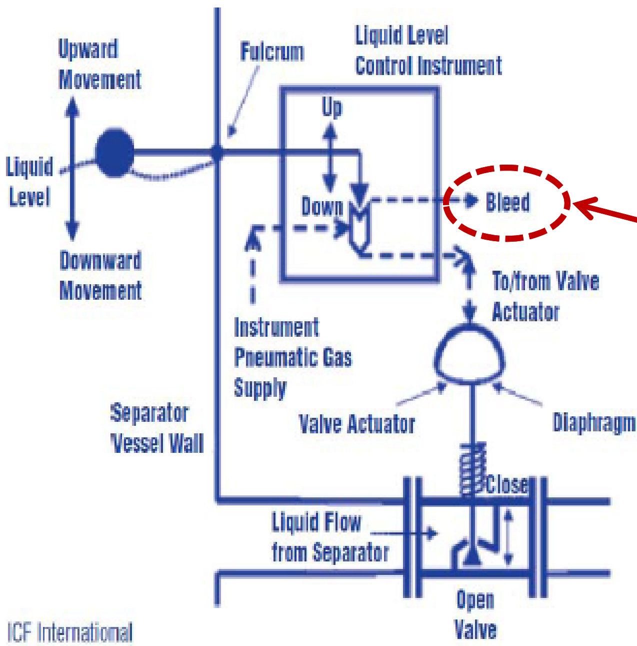
Courtesy Scott Baker, PJM

Flaring and venting of stranded NG

- 5.3 trillion cubic feet of natural gas flared annually
  - 5 quadrillion BTUs
  - 25% US electricity production





- Pneumatic devices use NG pressure to drive pumps, regulators, and valves & then vent
- > 20 million tons CO_2 eq. annually: 20-35% of production-related emissions

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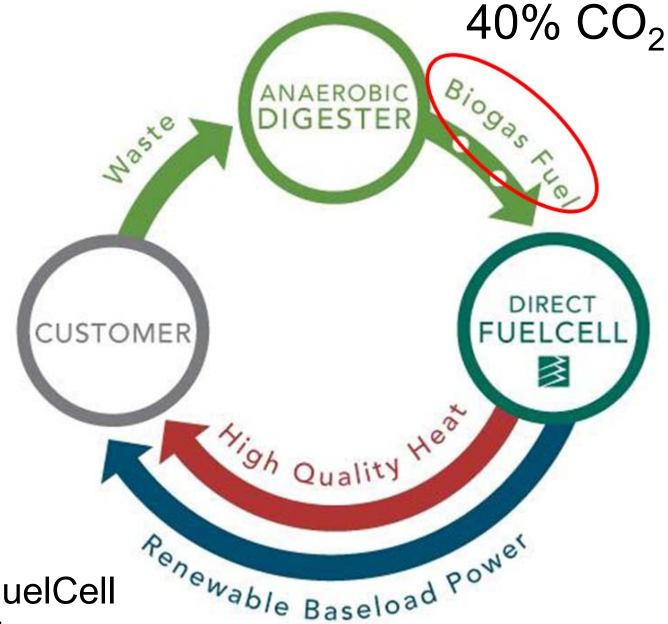
Source: World Bank, Global Gas Flaring Reduction Partnership, 2012

Low-carbon fuels enable low-GHG DG

1 Biogas

60% CH_4+
40% CO_2

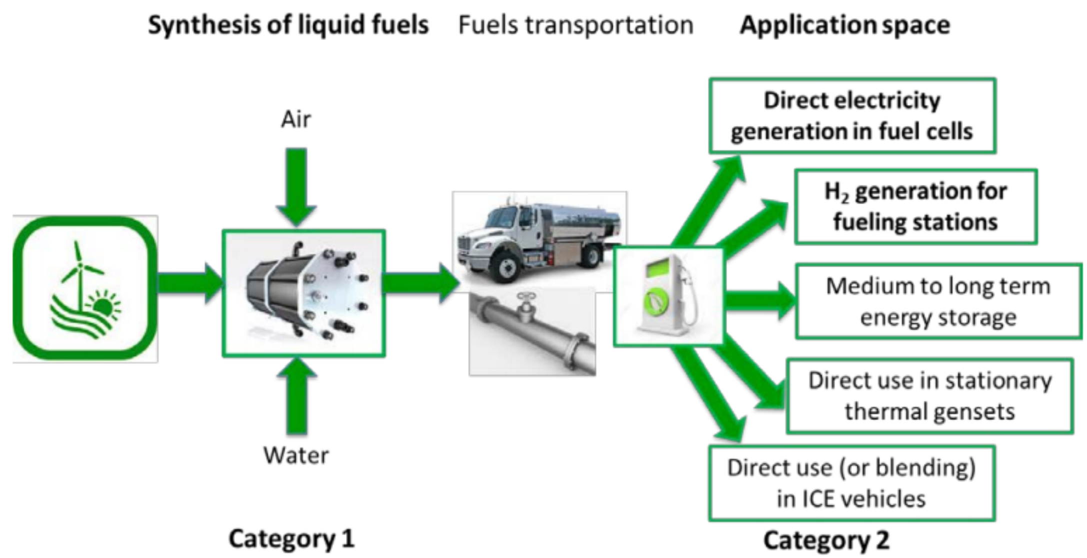


FuelCell Energy

2 Synthetic NG via the Sabatier reaction

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$

3 Carbon-neutral liquid fuels (REFUEL)



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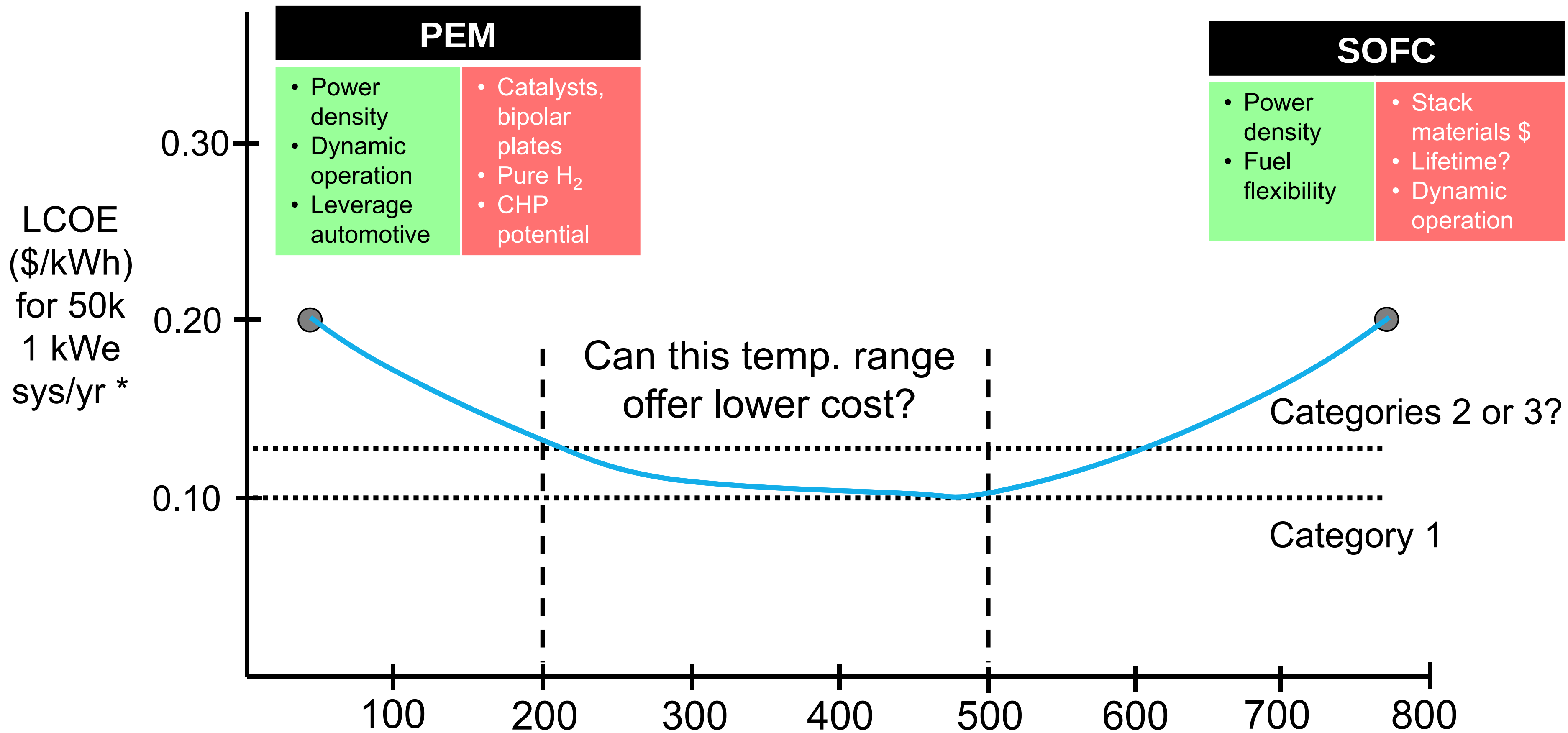
REBELS hypothesis: cost is lower at 200-500°C



PEM, SOFC data: based on "Manufacturing Cost Analysis of Stationary Fuel Cell Systems," SA (2012)

* Based only on direct manufacturing costs

Intermediate temperature fuel cells (ITFCs)

REBELS program focus is 200 to 500°C

	Compared to Low T	Compared to High T
Strengths	• Potentially lower PGM • Less fuel processing • Less cooling required	• Cheaper interconnects & seals • Fewer CTE problems • Greater ability to ramp/cycle
Weaknesses	• Longer start-up • Capability for dynamic operation less clear	• Higher resistance & overpotentials • Fuel reforming issues

REBELS focus

REBELS Program Categories

The 200 to 500°C temperature range will enable new chemistries, materials, and functionalities:

1 — ITFC

Efficient, reliable small power systems

- Entry markets valuing reliability, including DoD
- Low cost CHP: > 80% efficiency, fewer CO_2 emissions

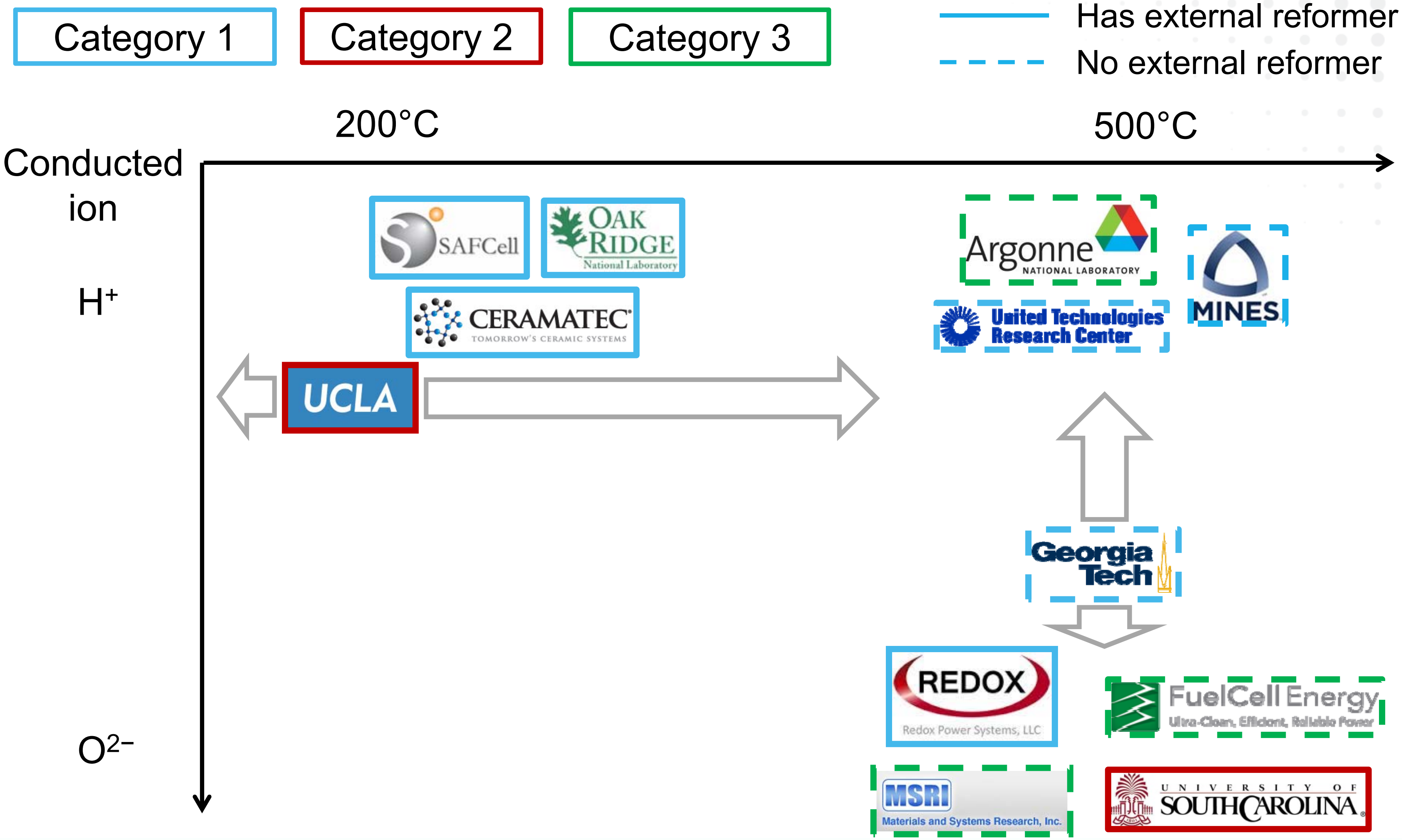
2 — Fuel Cell + Additional Functionality

Fuel cell with integrated battery mode for faster response to transients

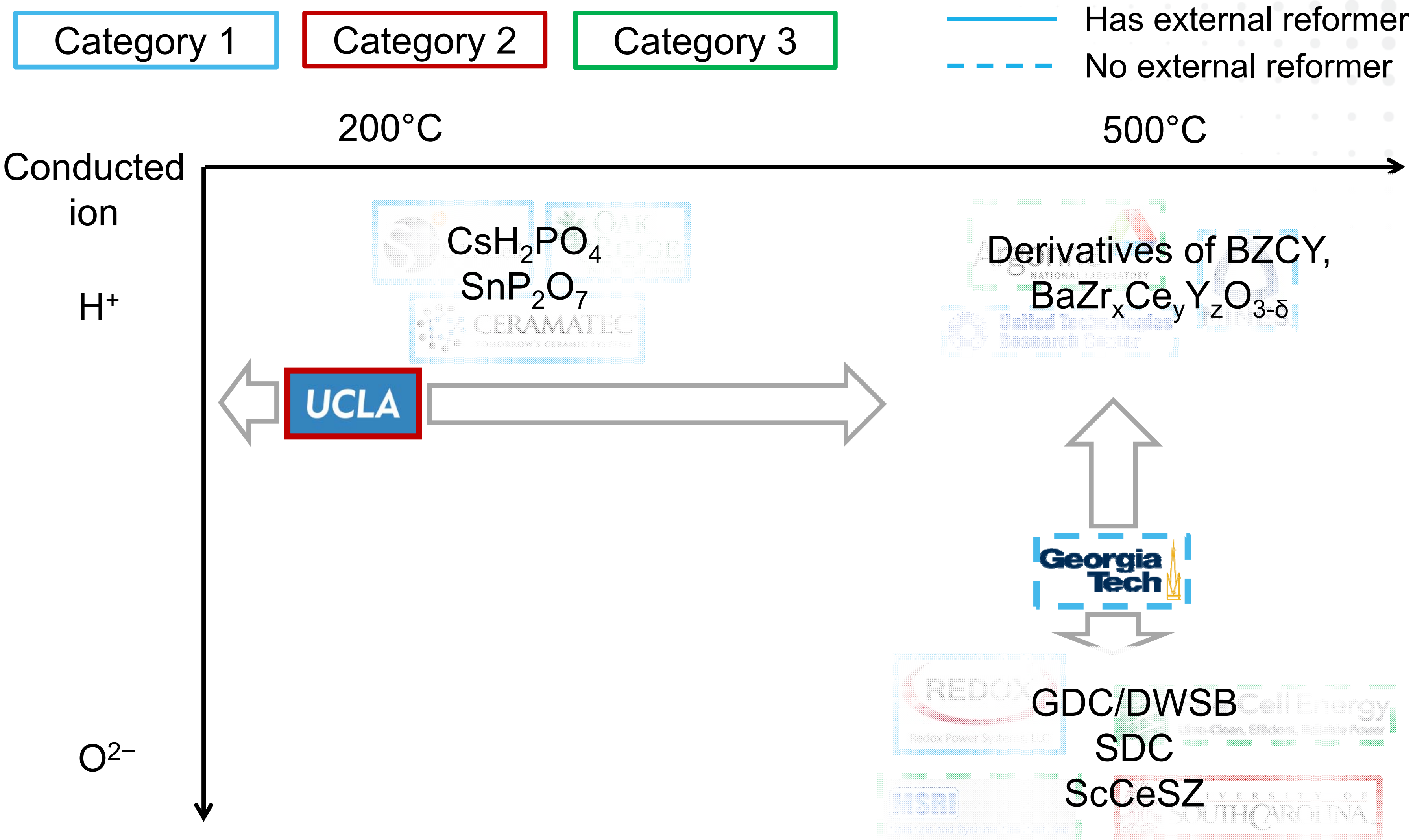
3 — Fuel Cell + Additional Functionality

Fuel cell with ability to convert natural gas to liquid fuels or valuable products

REBELS program technical overview



REBELS program technical overview



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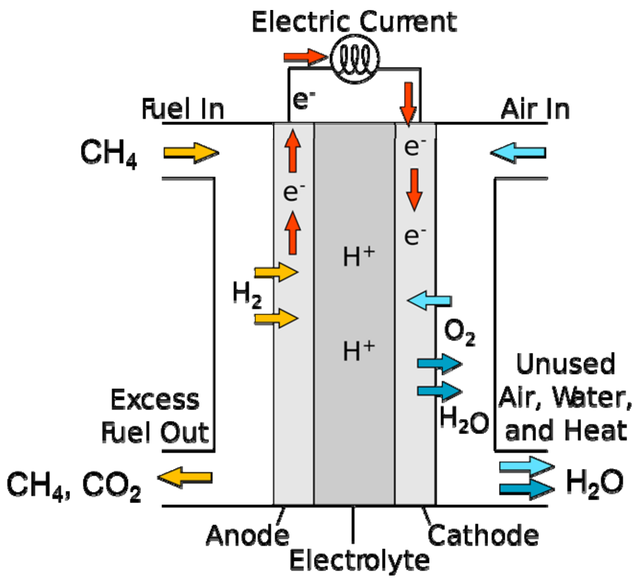
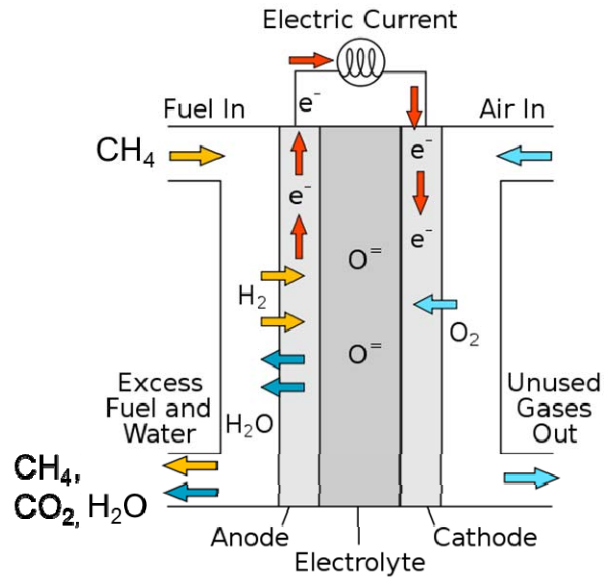
Proton vs. oxygen ion conductors



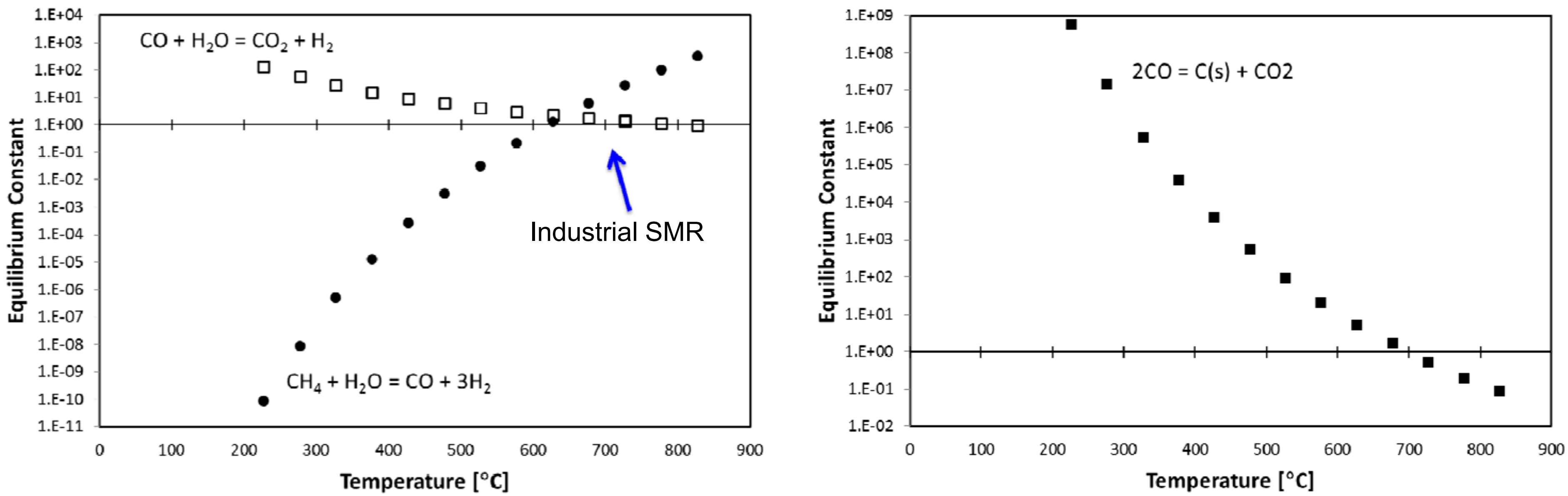


	Proton conductor	Oxygen ion conductor
Activation energy (eV)	0.2 - 0.4	0.7 - 0.9
System impact	• Water formed on cathode side, need to pipe to anode to humidify • Removing protons shifts equilibrium away from coke formation	• Water formed on anode side; can be self-humidifying • Delivers O_2 to mitigate coking • Dilutes the fuel

Methane reforming at 500ºC risks coking

Steam reforming is typically a high temperature process

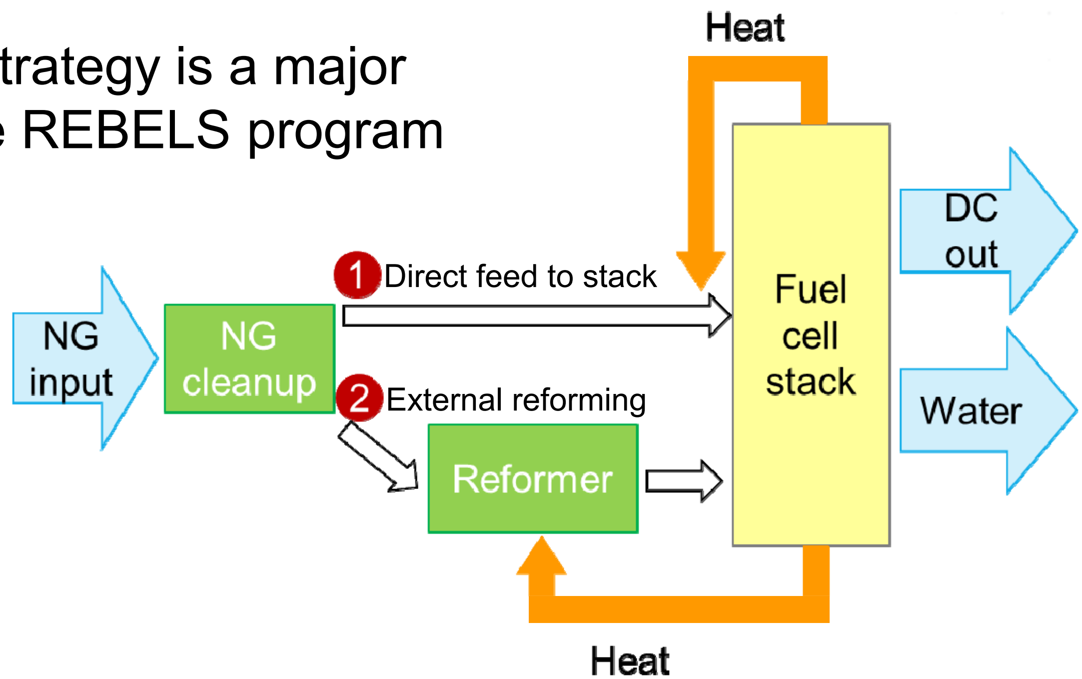
Coking is favored at lower temperatures



D. Matuszak

External vs. internal fuel reforming

Reforming strategy is a major theme of the REBELS program

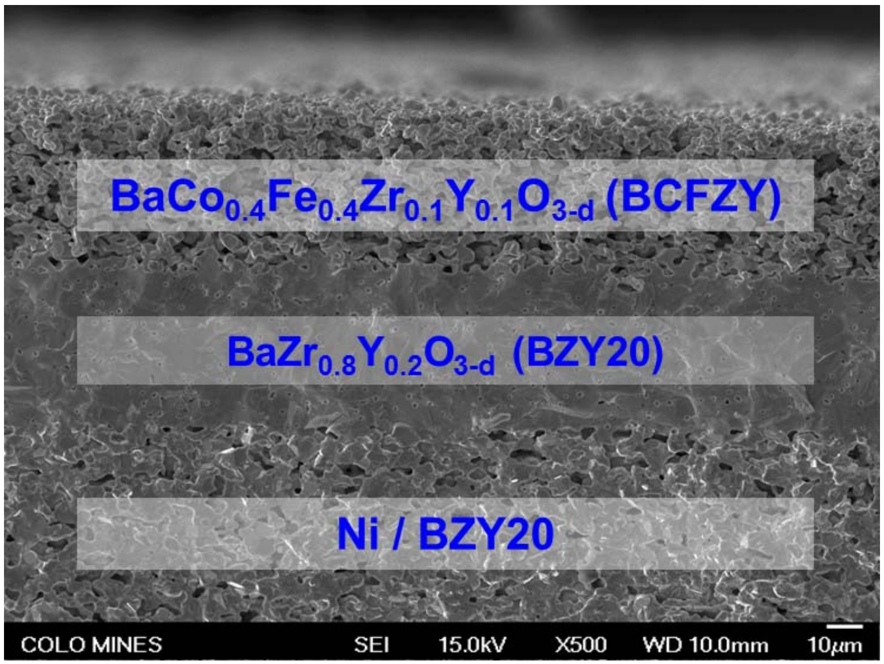


Internal reforming pros and cons

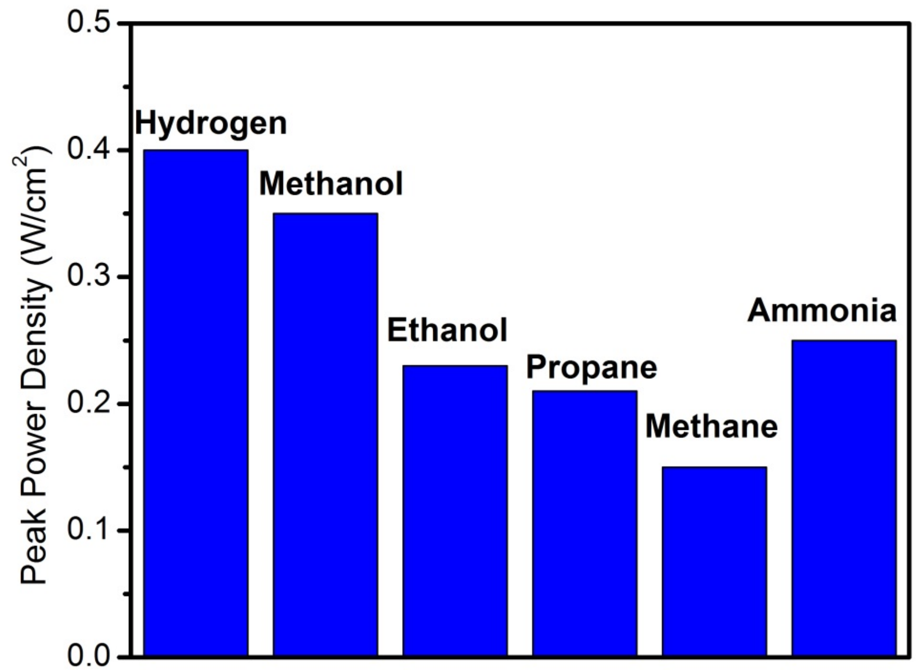
Pros	• Reduce capex, esp. for smaller systems • Endothermic reaction helps thermal management
Cons	• Must carefully manage steam:fuel ratio • Need NG cleanup operations • Long-term degradation?

Cat. 1: CSM runs at 500ºC on several fuels

Stack repeat unit



Peak power density at 500 ºC
No pre-reforming of the fuel



Voltage stability shown for hundreds to thousands of hours on wet methane

Data courtesy R. O'Hayre, Colorado School of Mines

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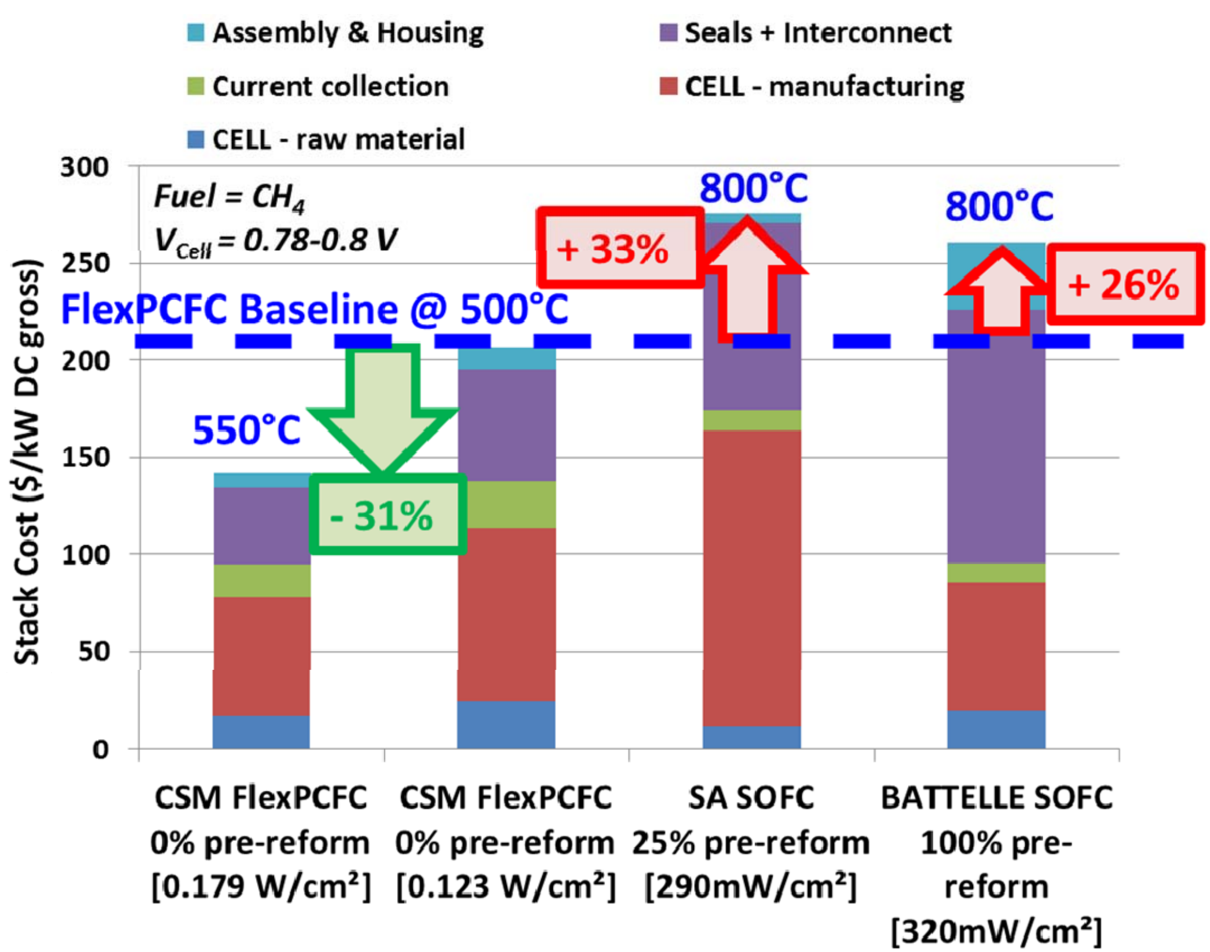
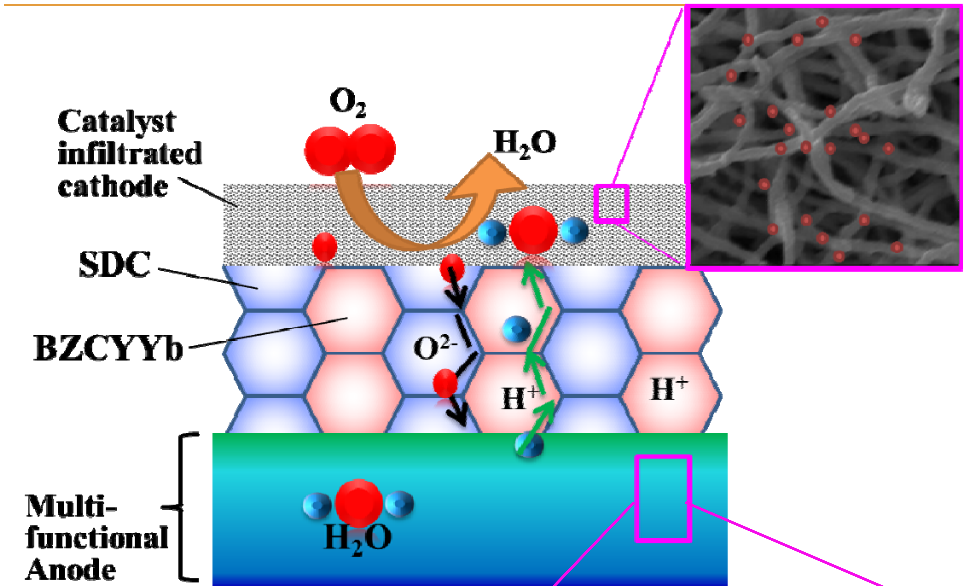
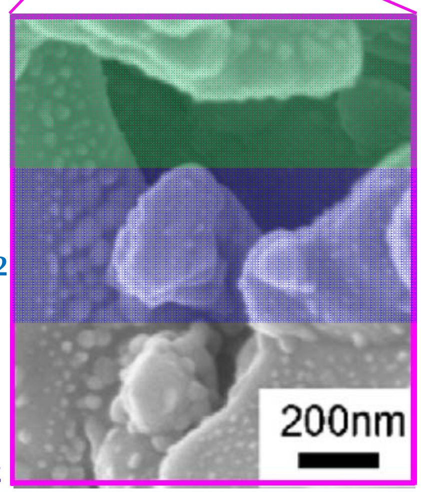
Cat. 1: CSM cost model shows benefits



Battelle: "Manufacturing Cost Analysis of 1 kW and 5 kW Solid Oxide Fuel Cell (SOFC) For APU Applications" (2014)
Strategic Analysis, Inc: "Manufacturing cost analysis of stationary fuel cell systems" (2012)

Cat 1: Georgia Tech runs on dry methane at 500°C





Fuel oxidation

$H_2 \rightarrow 2H^+ + 2e^-$

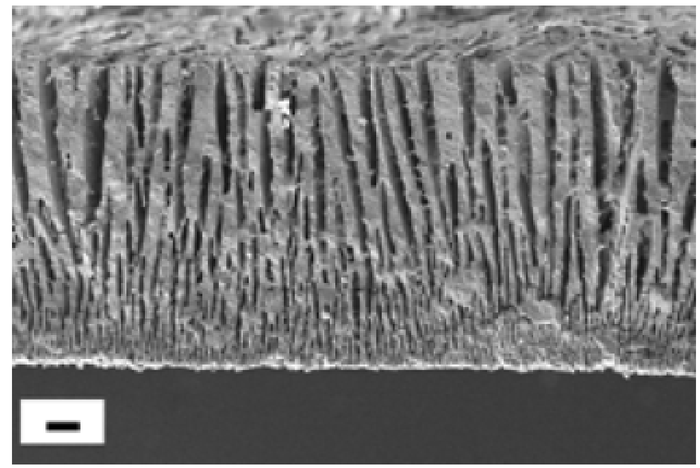
WGS

$H_2O + CO \rightarrow H_2 + CO_2$

Reforming

$CH_4 + H_2O \rightarrow 3H_2 + CO$

$CH_4 + CO_2 \rightarrow 2CO + 2H_2$

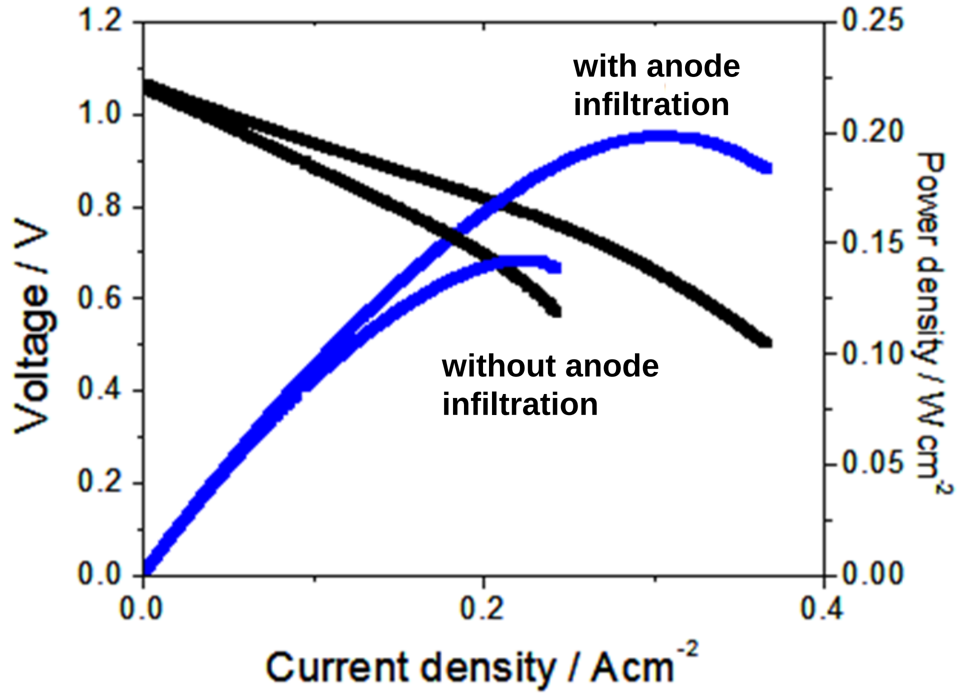


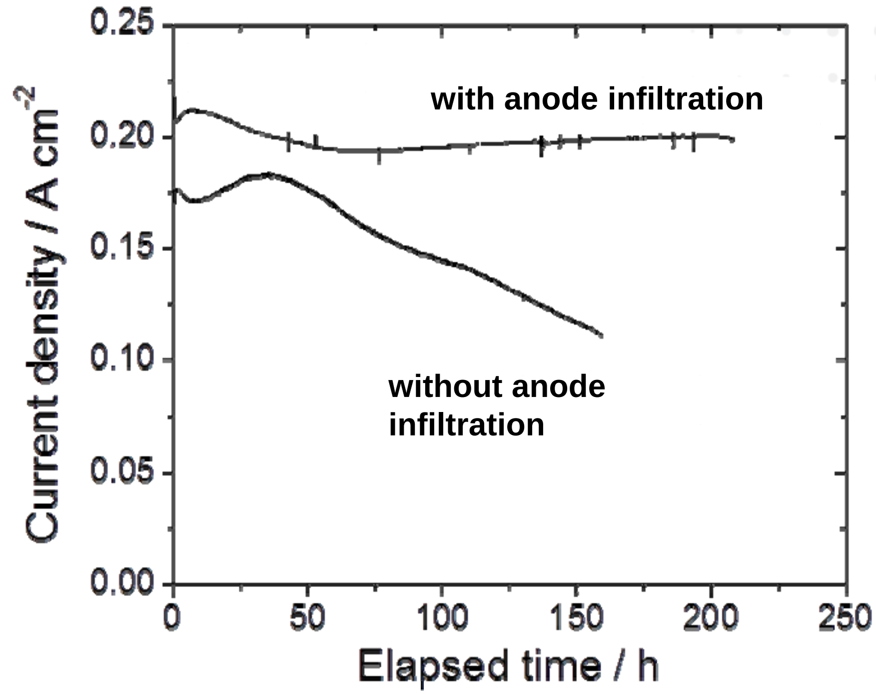
Cross-section of anode made via freeze casting

arpa·e CHANGING WHAT'S POSSIBLE — Georgia Institute of Technology — THE UNIVERSITY OF KANSAS

Cat 1: Georgia Tech runs on dry methane at 500°C

Button cell: 500°C, 97%CH_4 / 3%H_2O, 5-10% fuel utilization

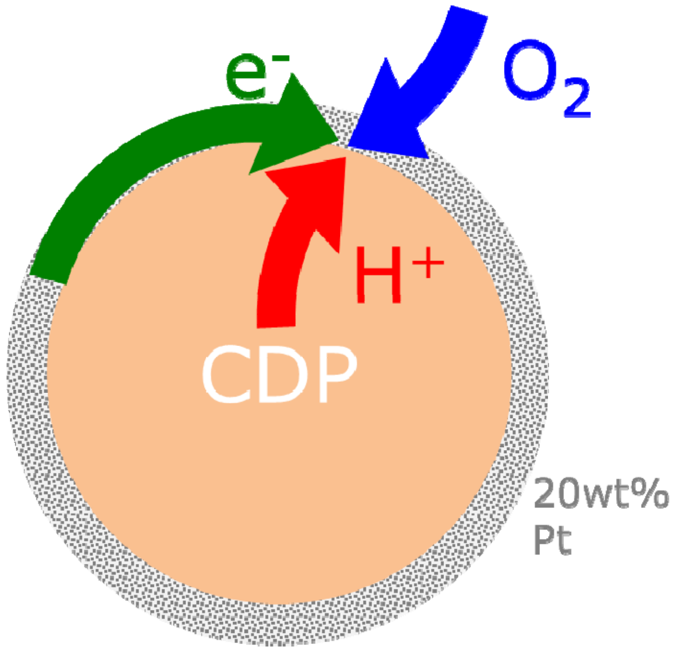




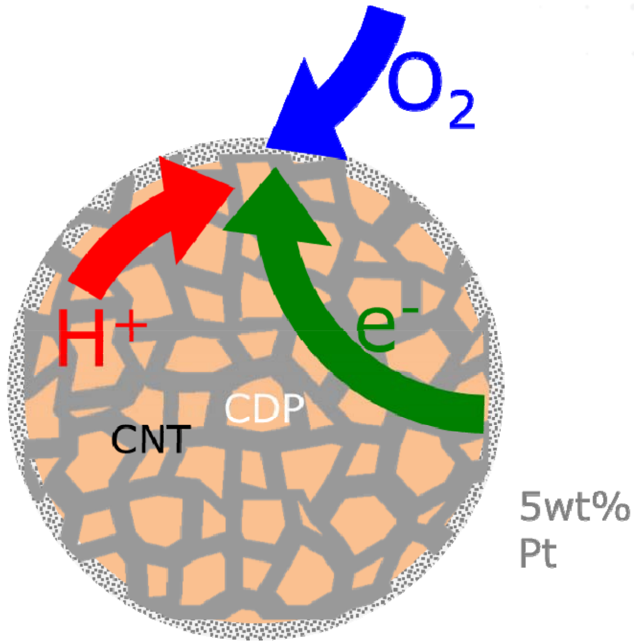
Data courtesy M. Liu, Georgia Tech

Cat 1: ORNL/UTK cut Pt by 4x in CDP electrode

State of the art: Pt is ORR catalyst and e$^-$ conductor; low CsH_2PO_4 (CDP) surface area

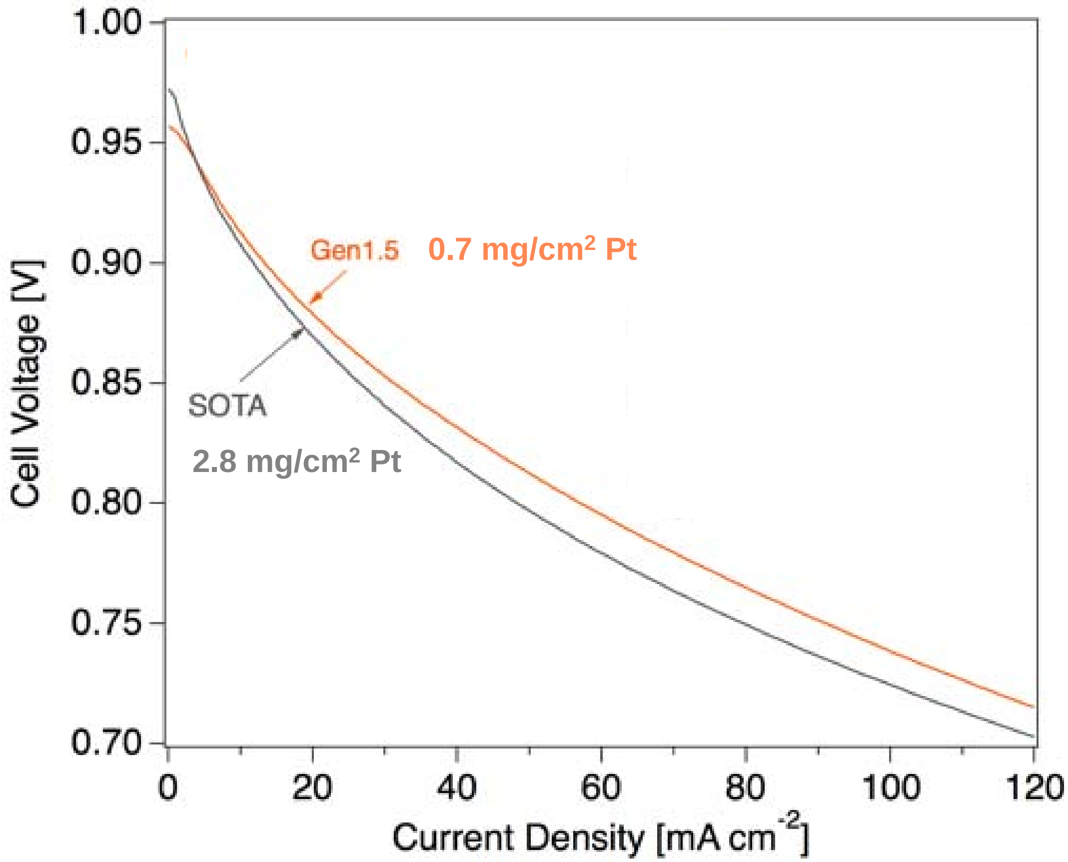


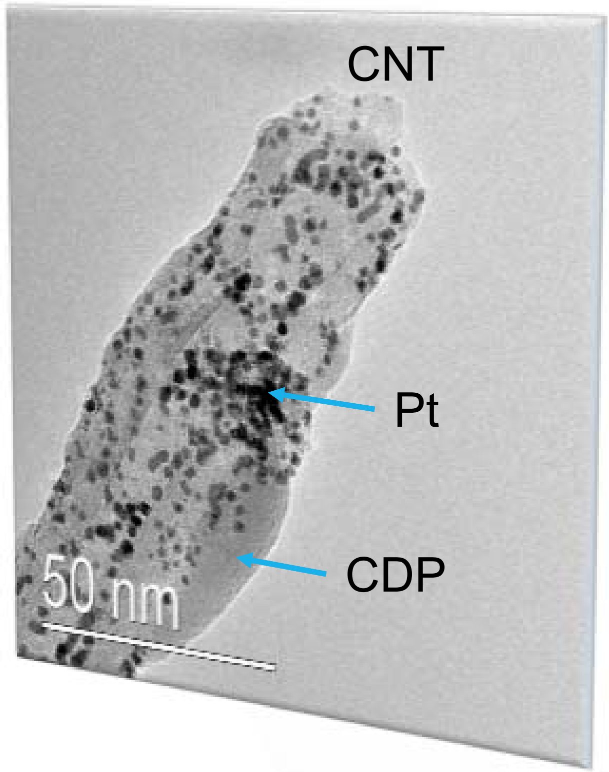
This project: Pt is ORR catalyst, CNTs are e$^-$ conductor, higher CDP surface area



Reminder: CsH_2PO_4 fuel cell runs at ~250ºC

Cat 1: ORNL/UTK cut Pt by 4x in CDP electrode





Data courtesy T. Zawodzinski and A. Papandrew, ORNL/UTK

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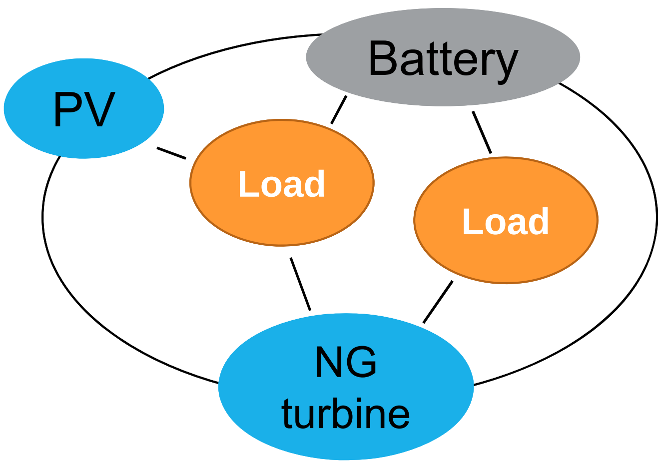
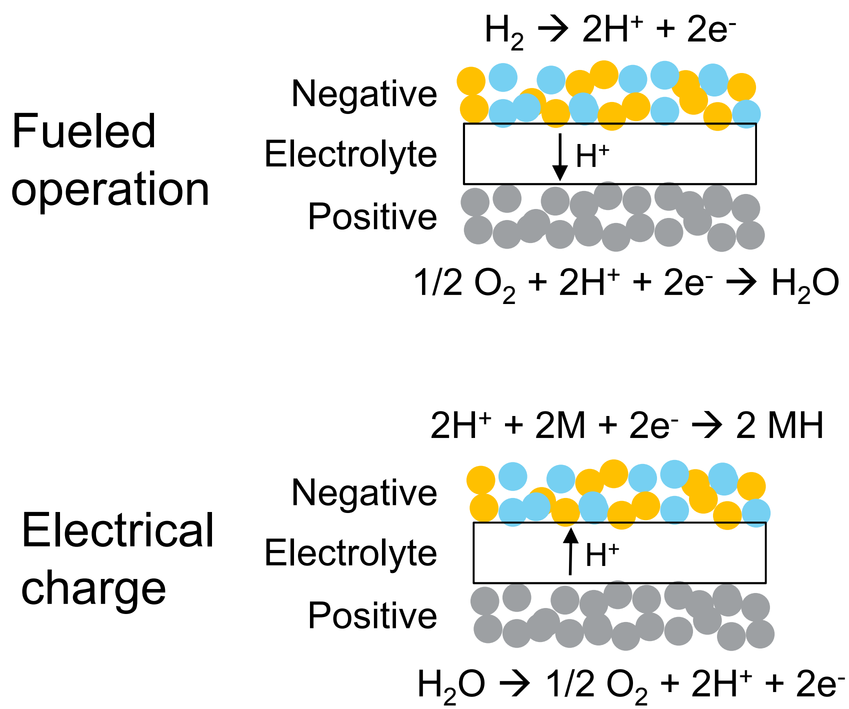
Category 2: hybrid generation & storage

Battery-like response via charge storage in an electrode

Today's Microgrids

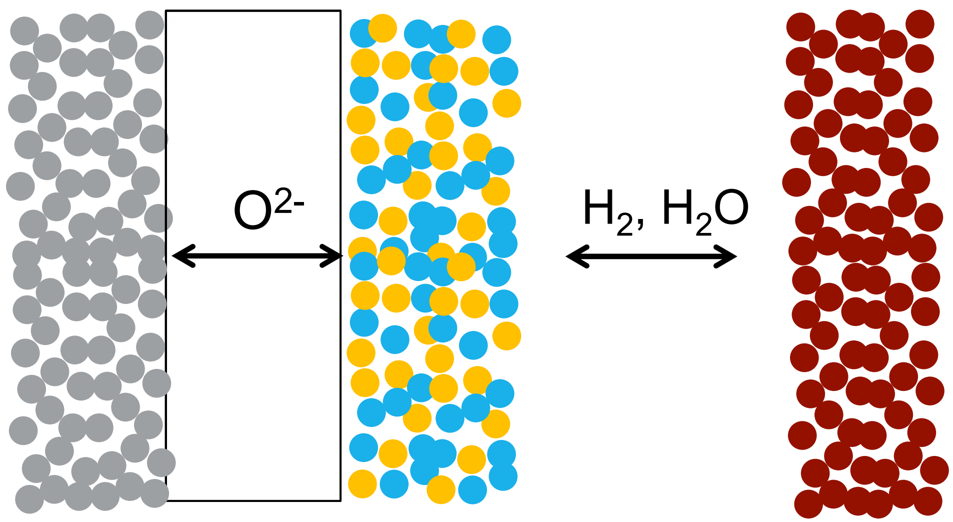


Charge Storage in a Fuel Cell



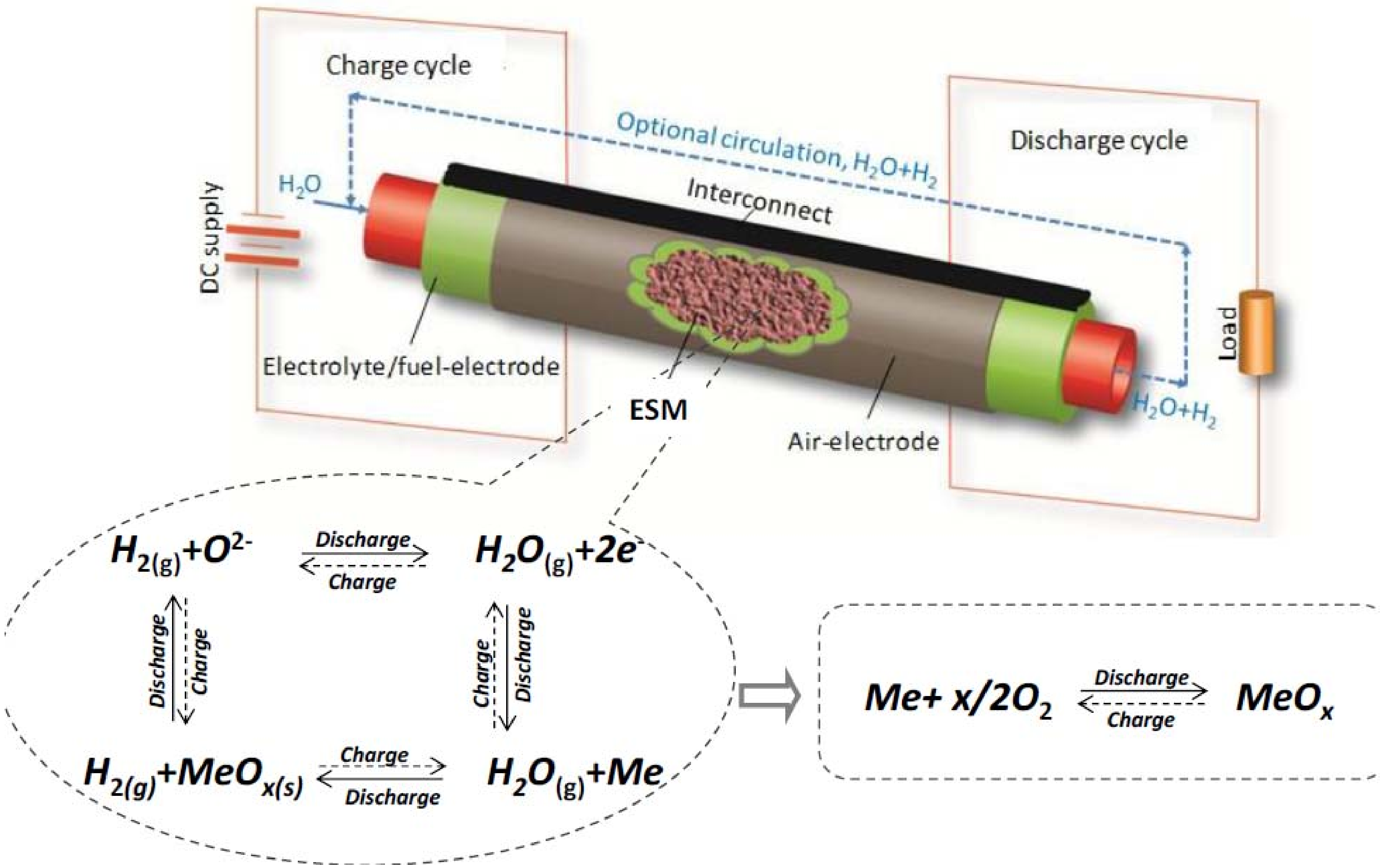
Univ SC demonstrates charge storage bed

Positive	Negative	Charge storage bed
$O_2 + 2e^- \leftrightarrow O^{2-}$	$H_2 + O^{2-} \leftrightarrow H_2O + 2e^-$	$2Fe + 3H_2O \leftrightarrow Fe_2O_3 + 3H_2$

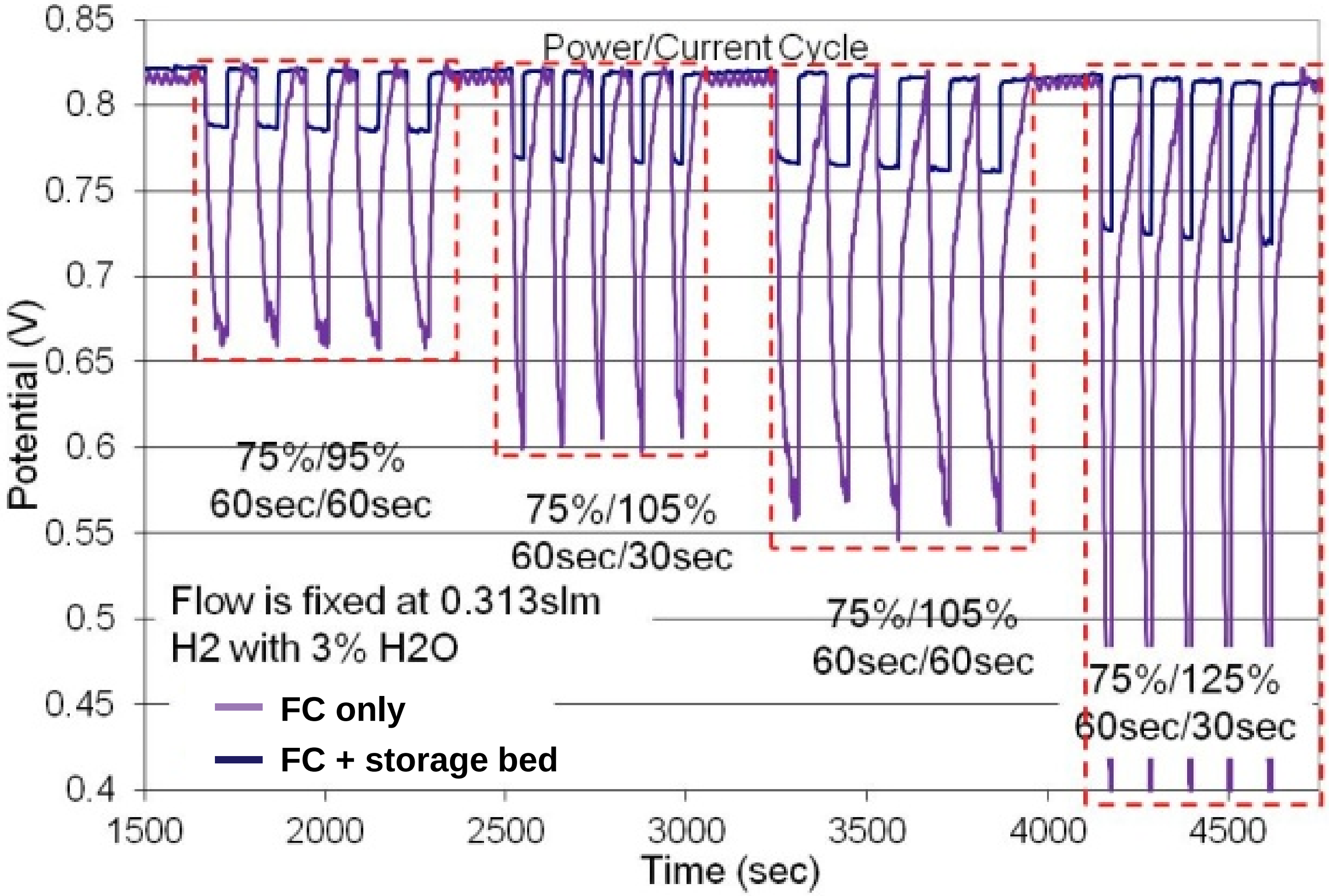


Bed composition set by gas-solid equilibrium

Cat 2: Univ SC demonstrates charge storage bed

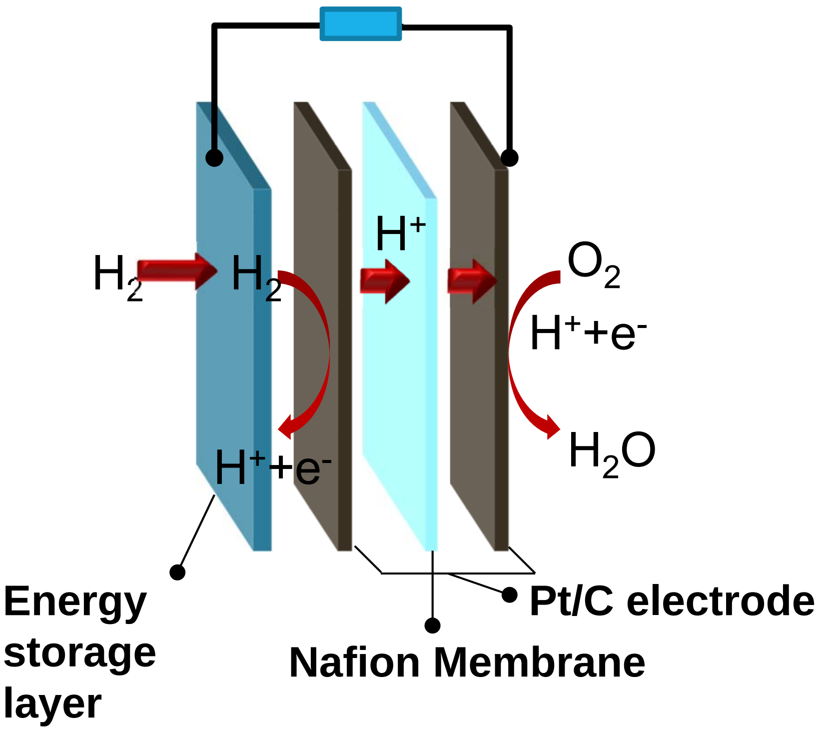


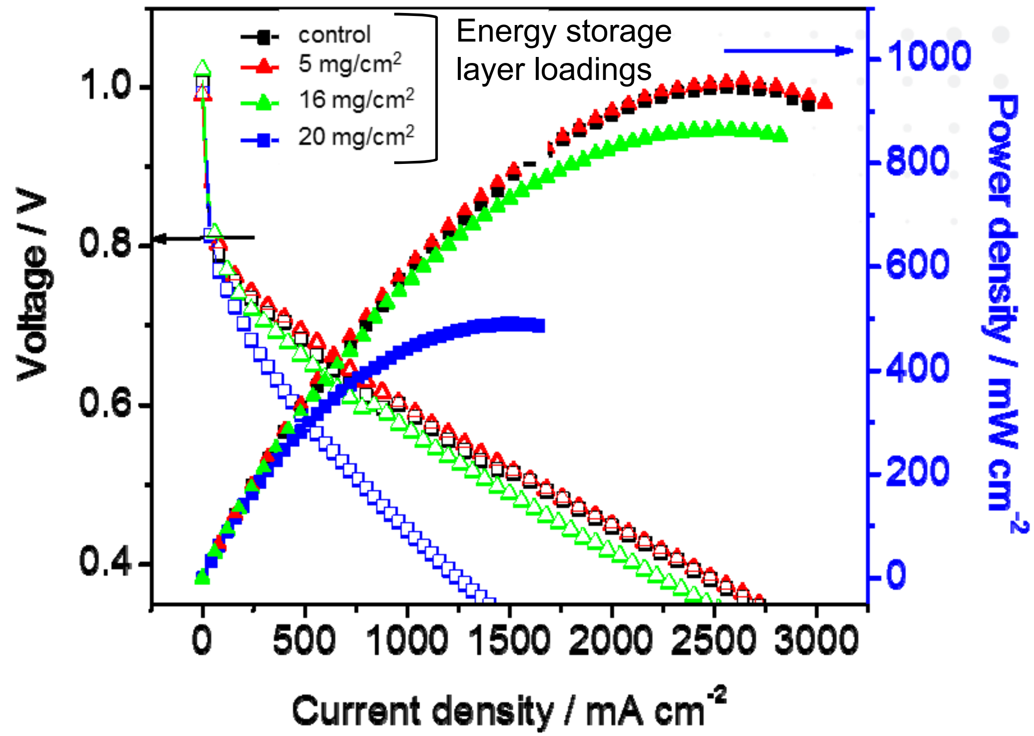
Cat 2: Univ SC demonstrates charge storage bed



Data courtesy K. Huang, Univ. of South Carolina

Cat. 2: UCLA shows electrode charge storage

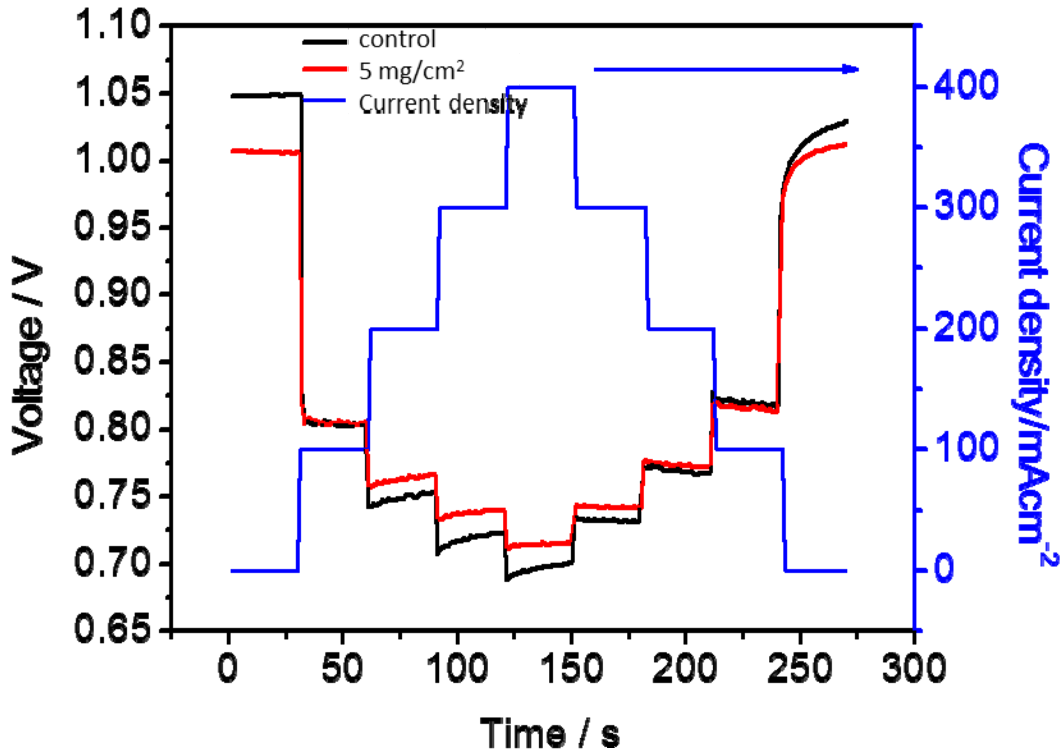




Temperature 30ºC, Pt loading in the anode 0.05 mg cm^{-2} , 0.4mg cm^{-2} in the cathode
Anode was supplied with 0.1L/min H_2, the cathode was supplied with 0.1L/min O_2

Cat. 2: UCLA shows electrode charge storage

Electrochemical response



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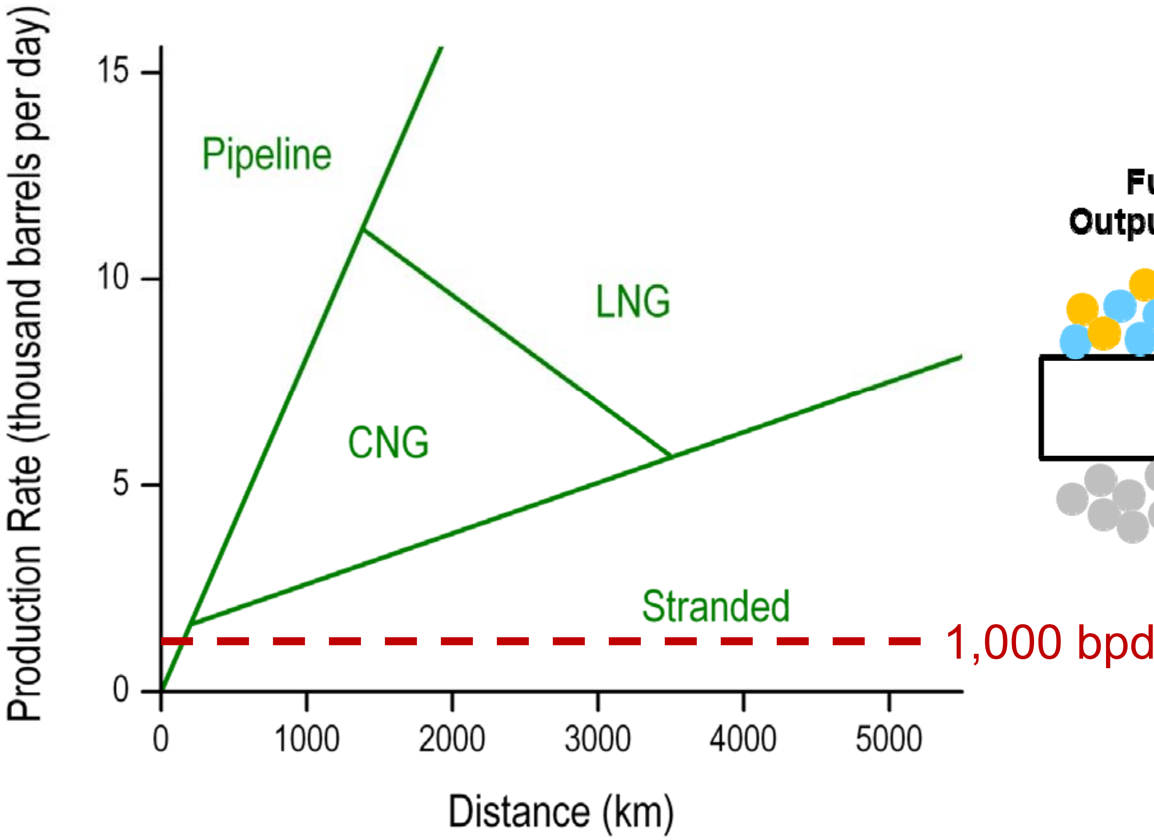
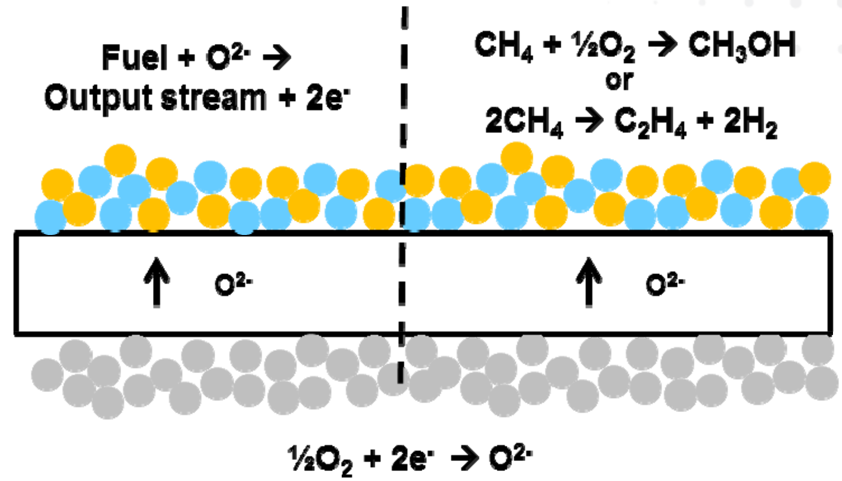
Category 3: converting NG to fuels or products





Source: D. Hawkins, TransOcean,Global, Gas Flaring Reduction Conference, Paris Dec 13-15, 2006

Cat 3: ANL fuel cell performance on H_2 fuel

(Ni/BZY anode; ~10-μm thick BCY electrolyte; Pt paste cathode)

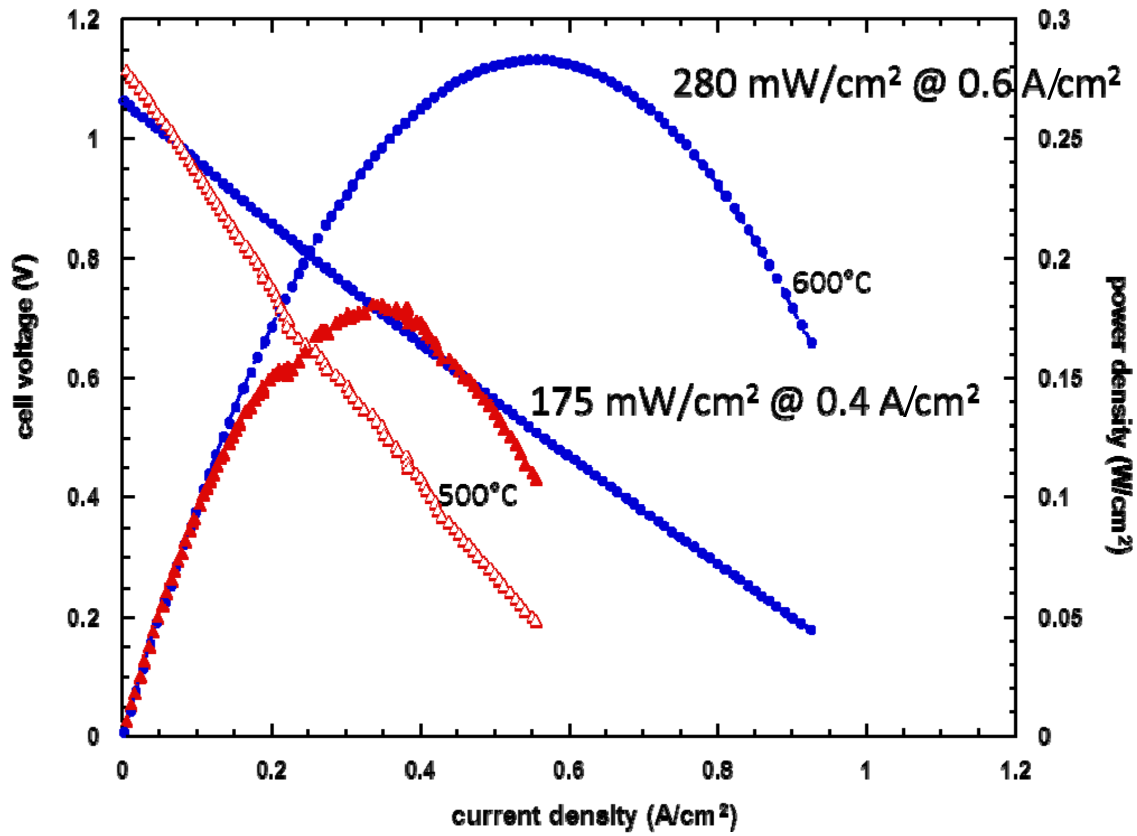


Figure courtesy T. Krause, ANL

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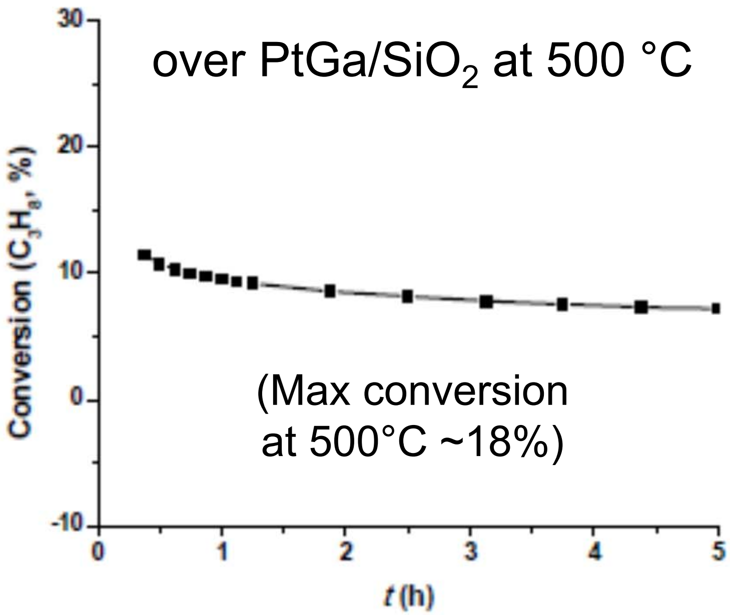
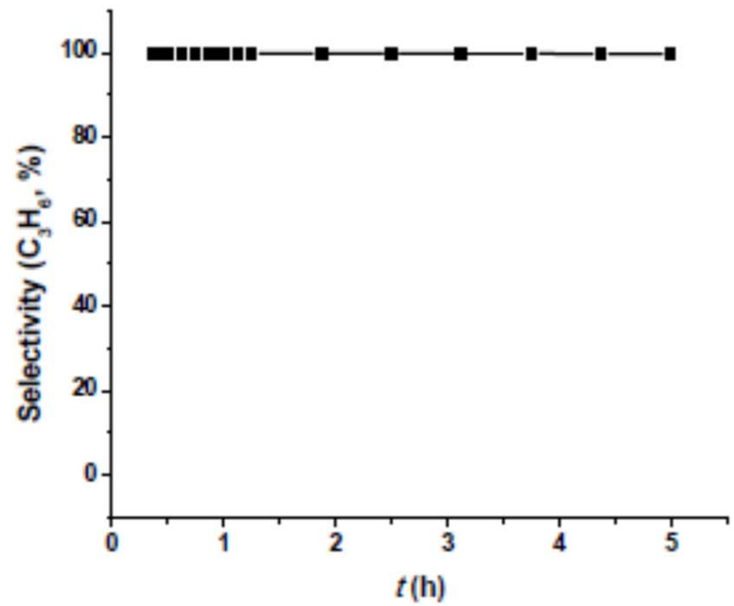
Argonne NATIONAL LABORATORY

ILLINOIS INSTITUTE OF TECHNOLOGY

Cat 3: ANL tubular reactor performance

- Reaction: propane dehydrogenation, $C_3H_8 \rightarrow C_3H_6 + H_2$





Figures courtesy T. Krause, ANL

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Lessons from REBELS after 1.5 years

- Can run on methane without an external reformer at 500°C both with (CSM) and without (GT) a steam co-feed.
- Several teams have cells with <1 Ohm-cm^2 ASR.
- Novel fuel cell functionality that partly achieves Category 2 and 3 visions has been shown.
- Techno-economic analyses need more work to show tradeoffs (power, material costs, lifetime, functionality, etc.)

Final goal: technical data and TEA to define the benefits (if any!) of REBELS over competing technologies.

- REBELS teams would benefit from NETL lessons learned.

ARPA-E Open Positions

Program Directors
Tech-to-Market Advisors
Fellows

[Apply Online]

Program Directors and T2M Advisors

Program Directors and T2M advisors serve 3-year terms

ROLES & RESPONSIBILITIES - PD

- Perform technical deep dive soliciting input from multiple stakeholders
- Present & defend program concept in climate of constructive criticism
- Actively manage portfolio projects from merit reviews through project completion
- Develop milestones and work "hands-on" with awardees in value delivery
- Represent ARPA-E as a thought leader in the program area

ROLES & RESPONSIBILITIES – T2M

- **Manage t**he Commercialization progress of project technologies
  - Manage project teams' T2M efforts through T2M Plans and jointly developed milestones
- **Advise:** support project teams with skills and knowledge to align technology with market needs
  - IP and competitor management
  - Value Chain and Market analysis
  - Product hypothesis
  - Economic analysis
  - Partner discovery and engagement

Fellows

ARPA-E semi-annually recruits new Fellows, who serve 2-year terms

ROLES & RESPONSIBILITIES

Identification of high-impact energy technologies

- Perform technical and economic analyses to identify high-impact energy technologies.
- Publish original research papers and reviews.

Active project advisement

- Actively advise & coach portfolio projects from merit reviews through project completion
- Extensive “hands-on” work with awardees.

Organizational support

- Review proposals for funding opportunities.
- Contribute to the strategic direction and vision of the agency.

ATTRIBUTES

- Ph.D. in science or engineering; strong analytical and communication skills; ability to work independently and across disciplines; leadership.
- ***A passion to change our energy future***

Questions

EXTRA SLIDES

CHANGING WHAT'S POSSIBLE

New(er) electrolytes for IT fuel cells

Not an exclusive list:

LT SOFCs

- Composite electrolytes with interfacial pathways
- Multilayer electrolytes

IT Proton Conductors

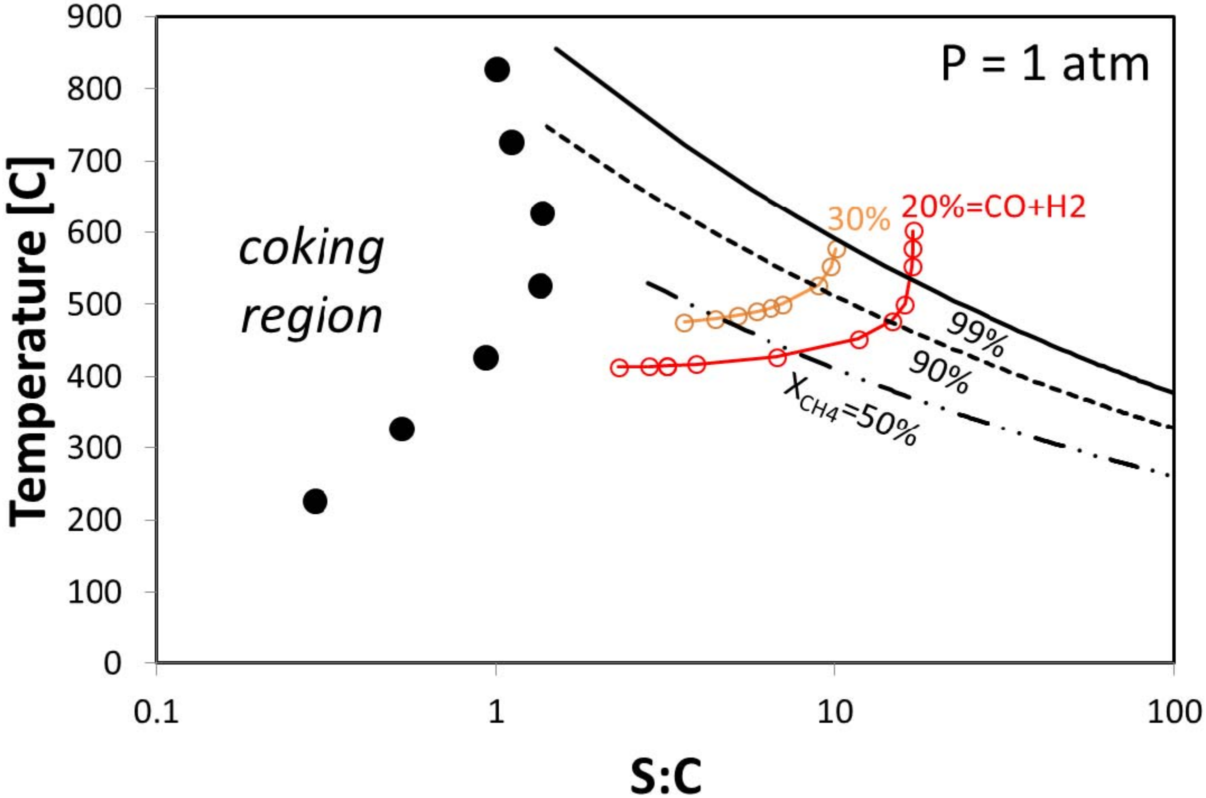
- $Ba(Zr, Ce, Y)O_3$
- Solid acid fuel cells
- Indium tin pyrophospate

Other Ionic Conductors

- HT alkaline
- HT phos acid
- LT molten carbonate

Thermodynamics of steam methane reforming

Steam:Carbon ratio is chosen to avoid coking,
achieve a target conversion and fuel concentration



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