Project DE-FE 0031940

Efficient, Reliable, and Cost-Effective Reversible Solid Oxide Cell Technology for Hydrogen and Electricity Production

and

Project DE-FE 0032107

Development of Novel 3D Cell Structure and Manufacturing Processes for Efficient, Durable and Redox Resistant Solid Oxide Electrolysis Cells

23rd Annual Solid Oxide Fuel Cell (SOFC) Project Review Meeting
October 25-27, 2022
Pittsburgh, PA

DE-FE0031940

Project Overview

- Project: Efficient, Reliable, and Cost-Effective Solid Oxide Cell Technology for Hydrogen and Electricity Production (DE-FE0031940)

- Project Objective: Develop and demonstrate reversible solid oxide cell (RSOC) technology with the three main specific objectives
  - (i) To validate design, materials and process of technology for both hydrogen and electricity production
  - (ii) To demonstrate operation of the technology at relevant conditions with improved performance, reliability and endurance
  - (iii) To confirm the cost effectiveness of the technology via a techno-economic assessment of a selected application

- DOE/NETL Project Manager: Ms. Sarah Michalik

- Project Team:
  - ❑ UCSD
    - *Center for Energy Research*: Dr. Nguyen Minh (PI)
    - *Department of Electrical Engineering and Center for Memory and Recording Research*: Dr. Eric Fullerton (Professor)
    - *Department of NanoEngineering*: Dr. Shirley Meng (Professor), Dr. Ping Liu (Professor)
  - ❑ OxEon
    - Dr. Elango Elangovan

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RSOC Technology

- RSOC technology for this project has two key elements
  - A compact, versatile and low-cost stack architecture: arrays of cell modules in electrical parallel and series connection
  - Superior-performance, fuel-flexible reversible cells

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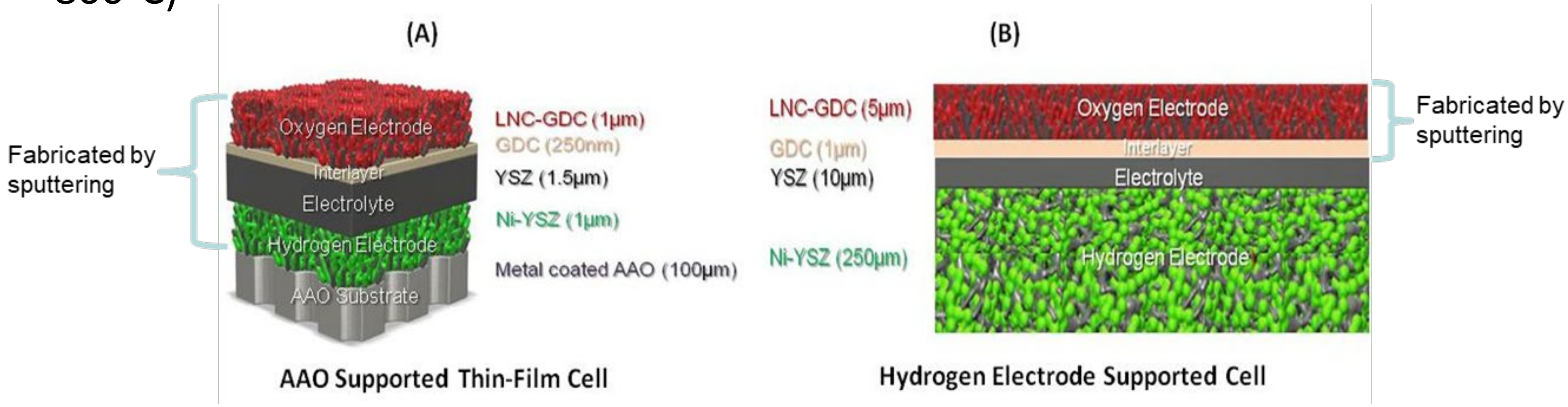
Cell Configurations

- Cell Structure: (A) Substrate supported thin-film (TF) reversible solid oxide cell (RSOC) (500˚-700˚C) and (B) Hydrogen electrode (HE) supported RSOC (700˚-800˚C)



- Cell and substrate materials:
  - Electrolyte : yttria stabilized zirconia (YSZ)
  - Hydrogen electrode: Ni-YSZ
  - Oxygen electrode: lanthanum nickel cobaltite (LNC)-gadolinium doped ceria (GDC)
  - Electrolyte/electrode interlayer: GDC
  - Substrate for TF-RSOCs: Metal-coated anodized aluminum oxide (AAO)

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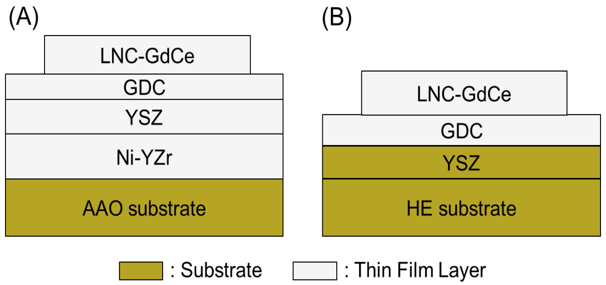
Cell Designs - Motivation

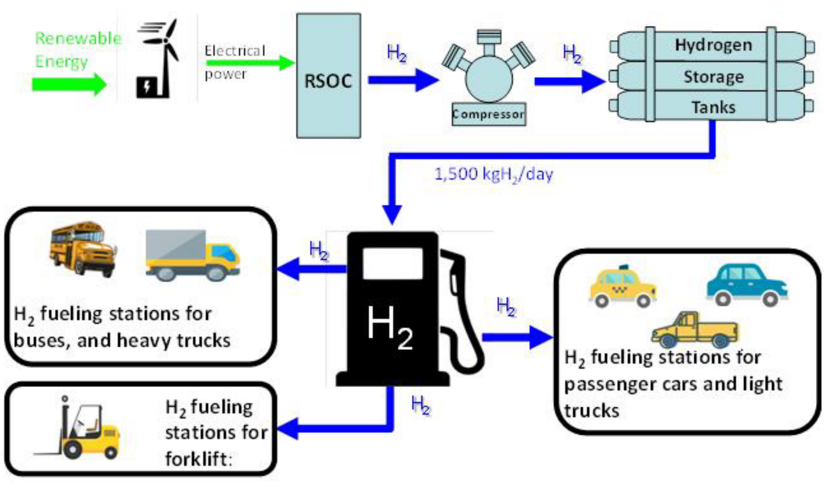


- Two types of cell configuration
  - Demonstrate the capability of the stack design to ***incorporate different types of cell operating at different temperatures***
  - Use the more advanced ***HE-supported cell as a backup with regards to risk mitigation***
  - Leverage and apply the development of ***sputtered high-performance oxygen electrodes for TF cells to HE-supported cells to improve performance*** as compared with state-of-the-art
- LNC-GDC oxygen electrode
  - ***A perovskite with high electrical conductivity***
  - LNC ($La_{0.97}Ni_{0.5}Co_{0.5}O_{3-\delta}$) contains ***no strontium***, thus ***unwanted Sr segregation and interactions with volatile Cr species to form strontium chromium oxides are avoided***

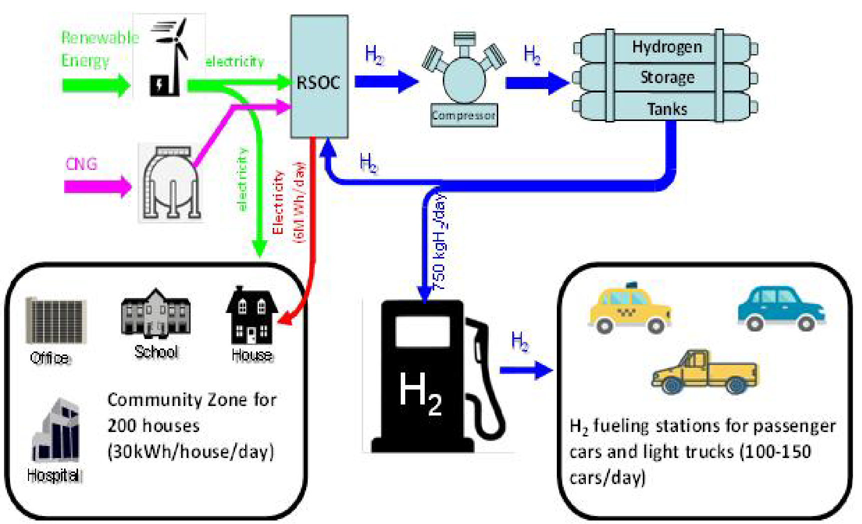
Application Selection and System Design and Analysis

Application Selection

- Reversible solid oxide cell (RSOC) systems selected
  - Small-scale distributed RSOC systems
  - Hydrogen production: 1,500 kg H_2/day
  - Power generation: 480 kW (on natural gas)
- Applications selected
  - On-site hydrogen fueling stations
    - for passenger car, and light trucks
    - for school buses, passenger buses, and heavy trucks
    - for forklifts
  - Distributed hydrogen/power systems
    - Hydrogen/power systems for low population areas/small towns/offices/buildings
    - Hydrogen/power systems for remote areas



On-site hydrogen fueling station



Distributed hydrogen/power system

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Technology Comparative Analysis

for Hydrogen Production

Specification	Solid oxide electrolysis	Alkaline electrolysis	PEM electrolysis	Steam Methane Reforming
Efficiency	● 90-100%	◐ 62-82%	◐ 67-82%	○ 50-65%
Feedstock	● Water, electricity	● Water, electricity	● Water, electricity	◐ CH_4, natural gas
Hydrogen Purity	● 99.9%	● 99.5-99.9%	● 99.9%	◐ 98-99%
Operation Flexibility	◐ 650-1000C, ambient to 25bar	○ 60-80C, ambient to 30bar, low current densities/production rates	◐ 50-100C, ambient to 200bar	○ 700-1000C, ambient to 20bar,low flexibility for production rates
CO2 Emissions	● None	● None	● None	○ 10 $kgCO_2/kgH_2$
Lifetime demonstrated	○ <10,000h	● 55,000-120,000h	● 20,000-100,000h	● 10,000-65,000h
Safety	◐ Hazards associated with hydrogen	◐ Hazards associated with hydrogen	◐ Hazards associated with hydrogen	◐ Hazards associated with hydrogen
Technology Readiness	◐ Prototype stage	● Commercial	◐ Pre-commercial	● Commercial

● : Advantageous or relatively better/higher or commercial

◐ : Relatively lower or moderate characteristic or prototype/precommercial

○ : Disadvantageous or relatively poor or development need

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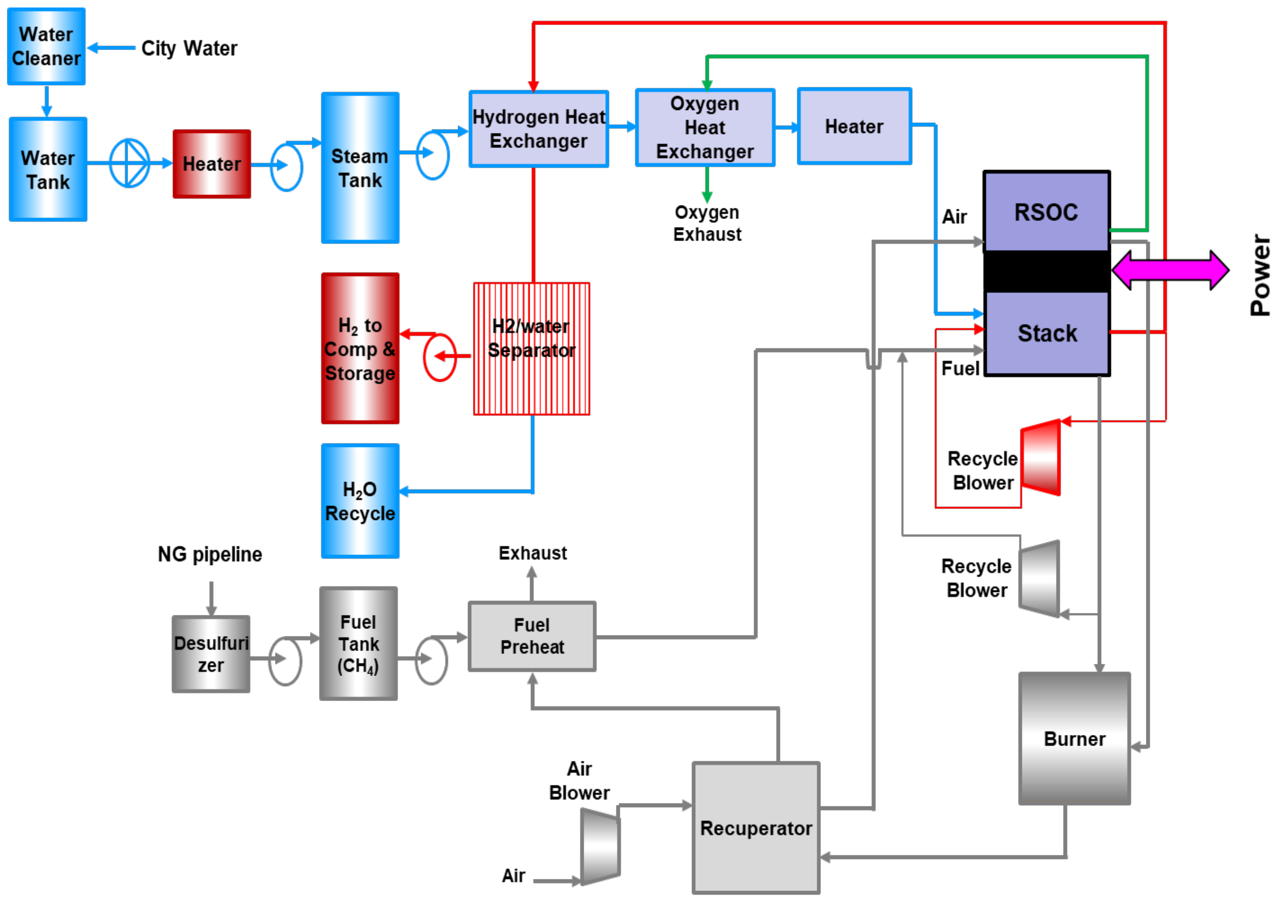
RSOC System Schematic



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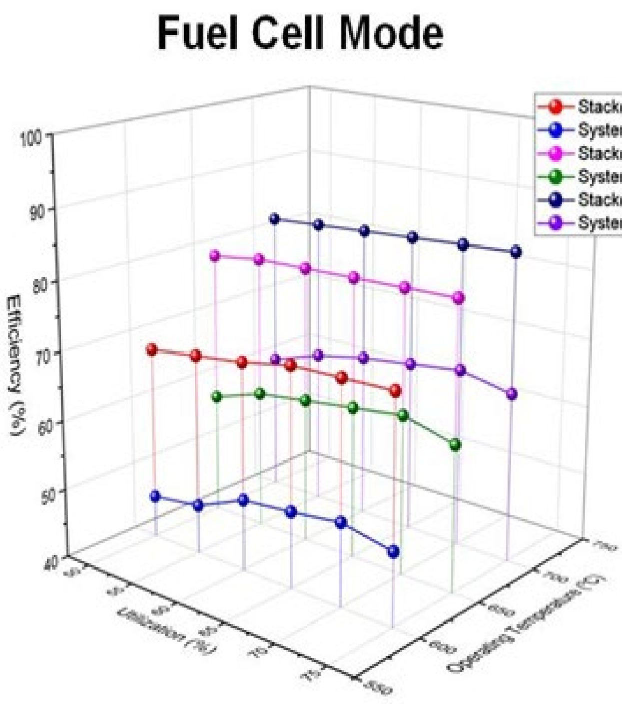
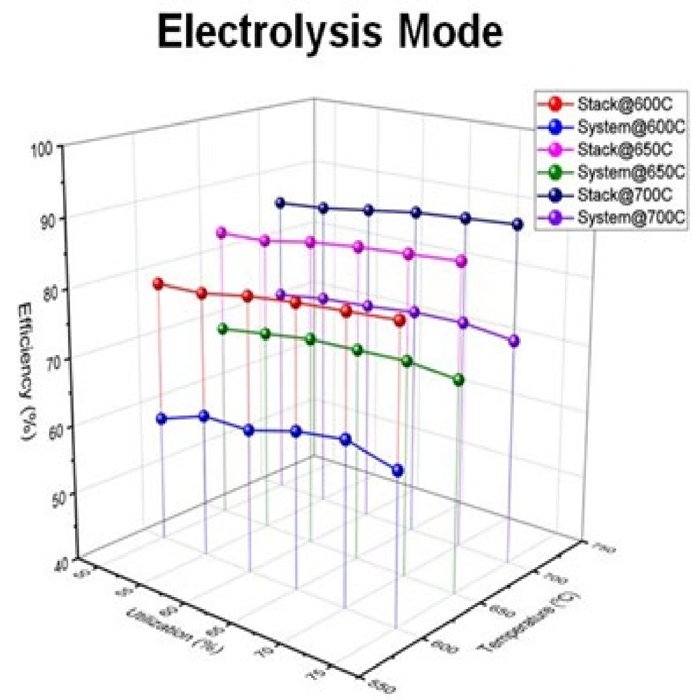
System Analysis - Reversible Operation





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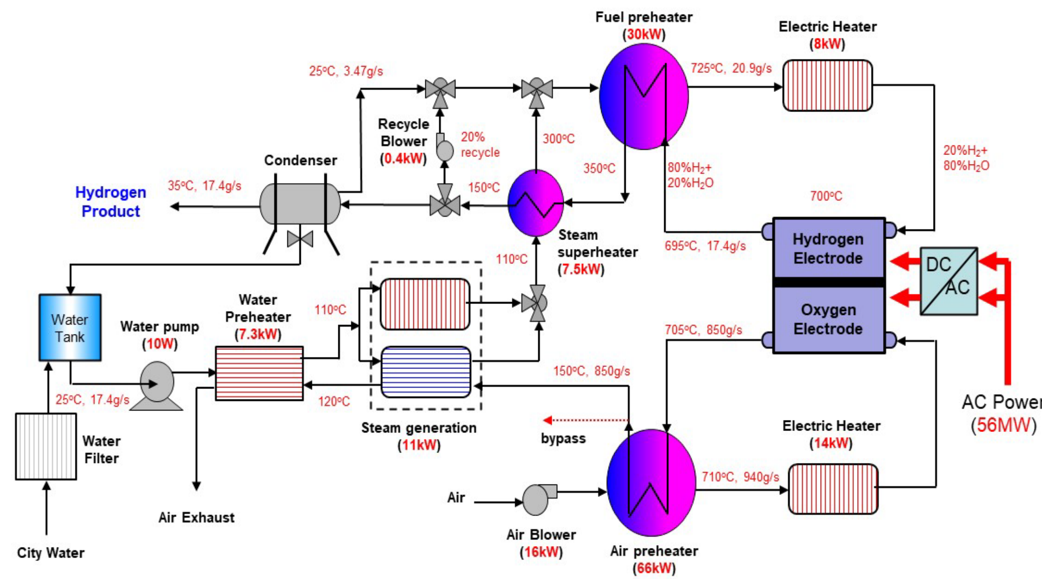
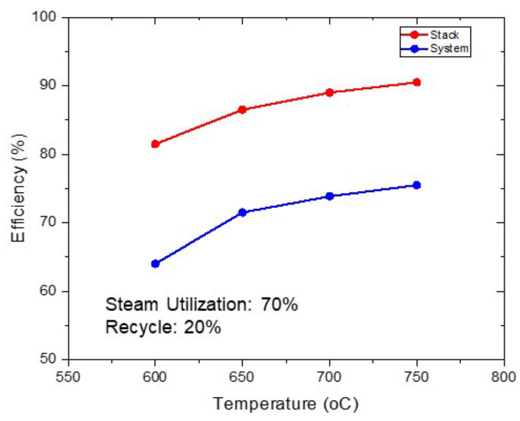
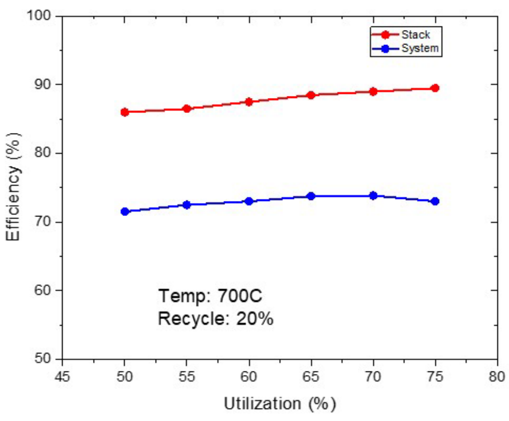
System Analysis - Electrolysis Mode Operation



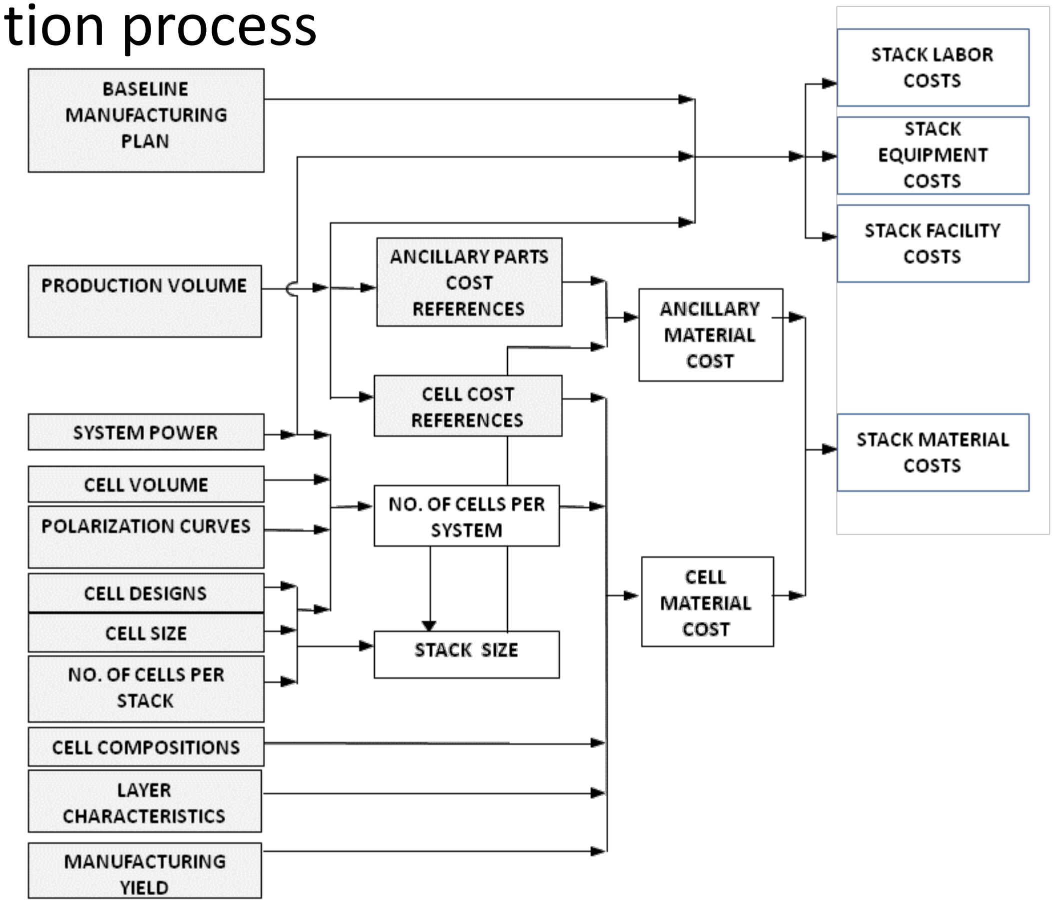




Techno-Economic Assessment

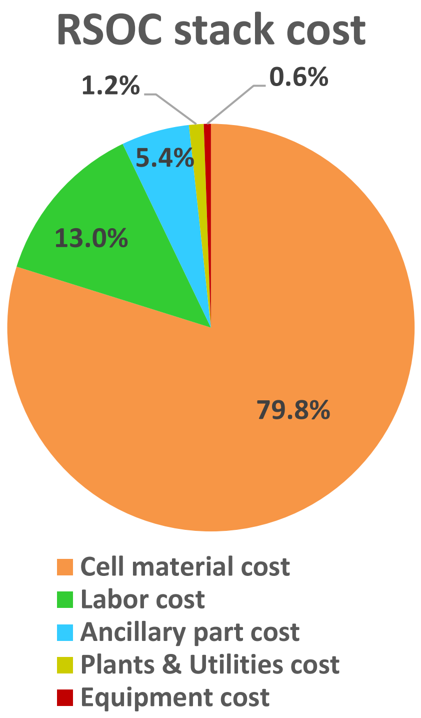
Stack Cost Estimation Process

- Key assumptions
  - Stack design being developed for the project
  - Laboratory cell performance obtained to date
  - Cell manufacturing in plant
  - System capable of producing 1,500 kg H_2/day
- Cost estimation process



Total Stack Cost Breakdown

	Cost ($/kW)	
Cell material cost	150.16	79.8%
Labor cost	24.51	13.0%
Ancillary part cost	10.18	5.4%
Plants & Utilities cost	2.18	1.2%
Equipment cost	1.06	0.6%
Total	**188.09**	



RSOC Cell Development

RSOC Cell Development - Key Activities

- Sputtering process scale-up studies
  - Demonstrate sputtering process scalability for cell fabrication
  - Improve film uniformity
- Metal coated AAO development
  - Development of metal coating process for AAO substrates
- Cell performance characterization
  - Electrochemical performance testing and performance mapping
  - Durability and long-term operation evaluation

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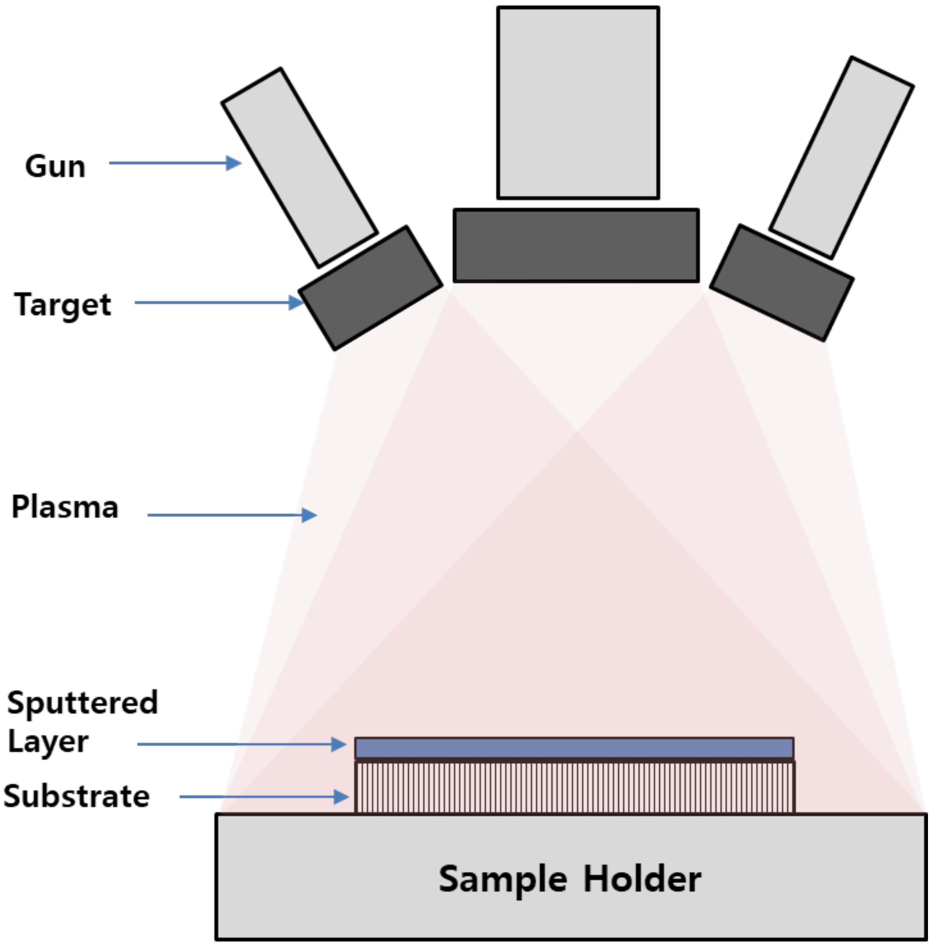
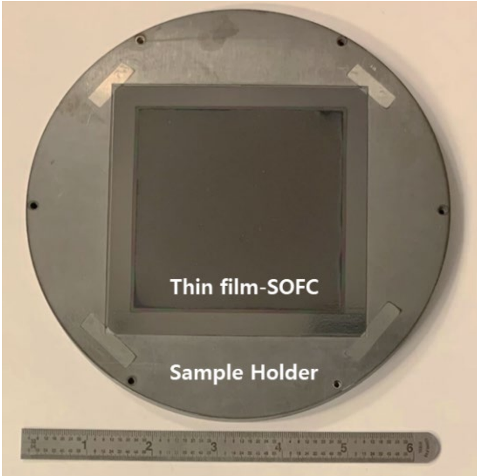
Sputtering Process





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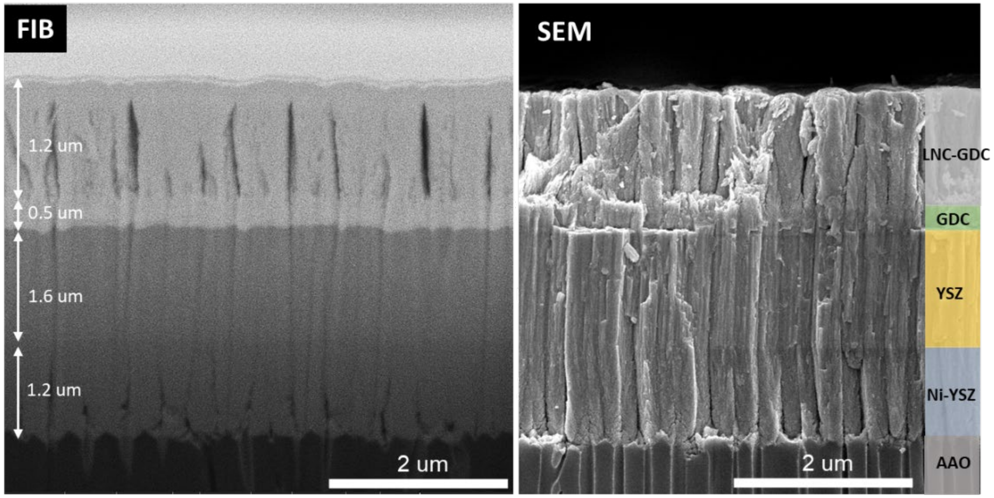
Sputtering Process Parameters

Key process parameters:

- Chamber pressure
- Target to substrate distance (TSD)
- Power
- Atmosphere



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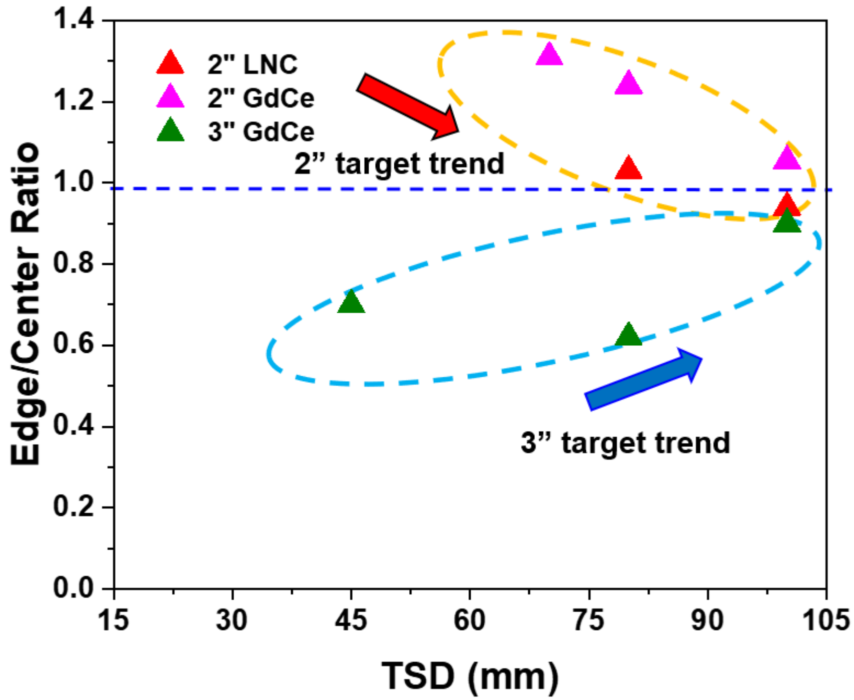
Sputtered Layer Thickness Uniformity

Deposited with Different TDS and Target Size



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Sputtering Recipe for Scale-up

Sputtering recipe for scale-up area deposition (over 5cmx5cm) is successfully developed

Component	Target Size/Materials	Power	Pressure	TSD
Hydrogen Electrode	3”Ni 2”GdCe	200WDC 200WDC	30mT	100 mm
Electrolyte	3”YSZ	200WRF	3mT	100 mm
Interlayer	3”GDC	200WRF	2mT	100 mm
Oxygen Electrode	3”GdCe 2”LNC	30WDC 200WRF	13.5mT	100 mm

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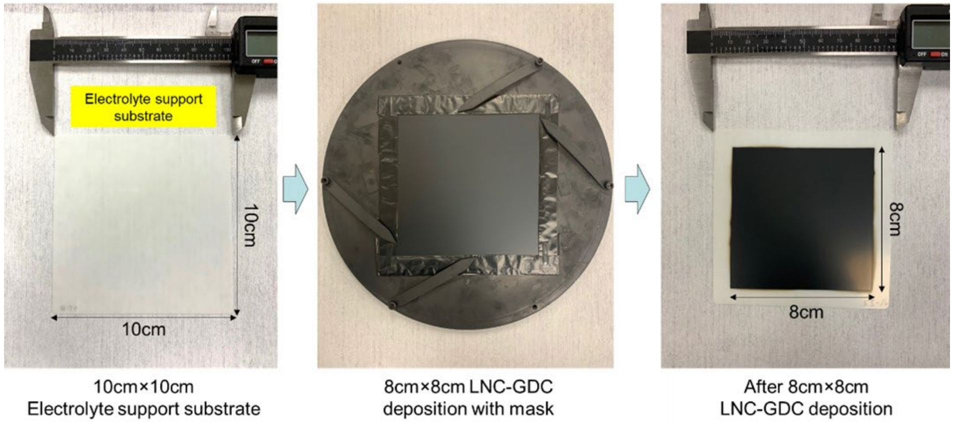
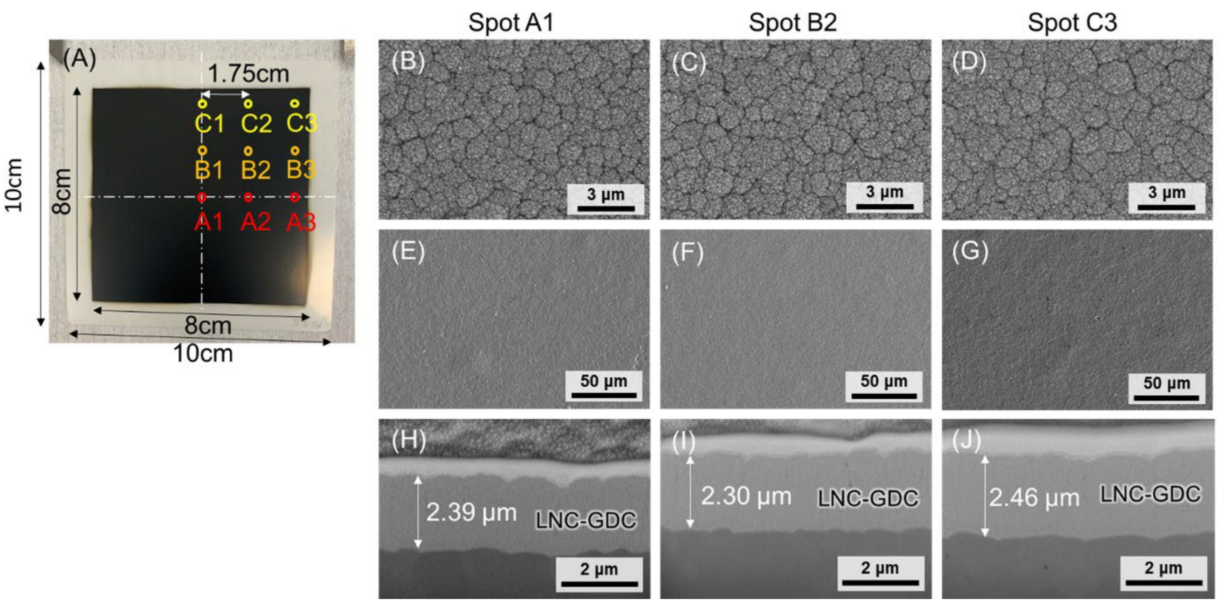
Fabrication Scaleup





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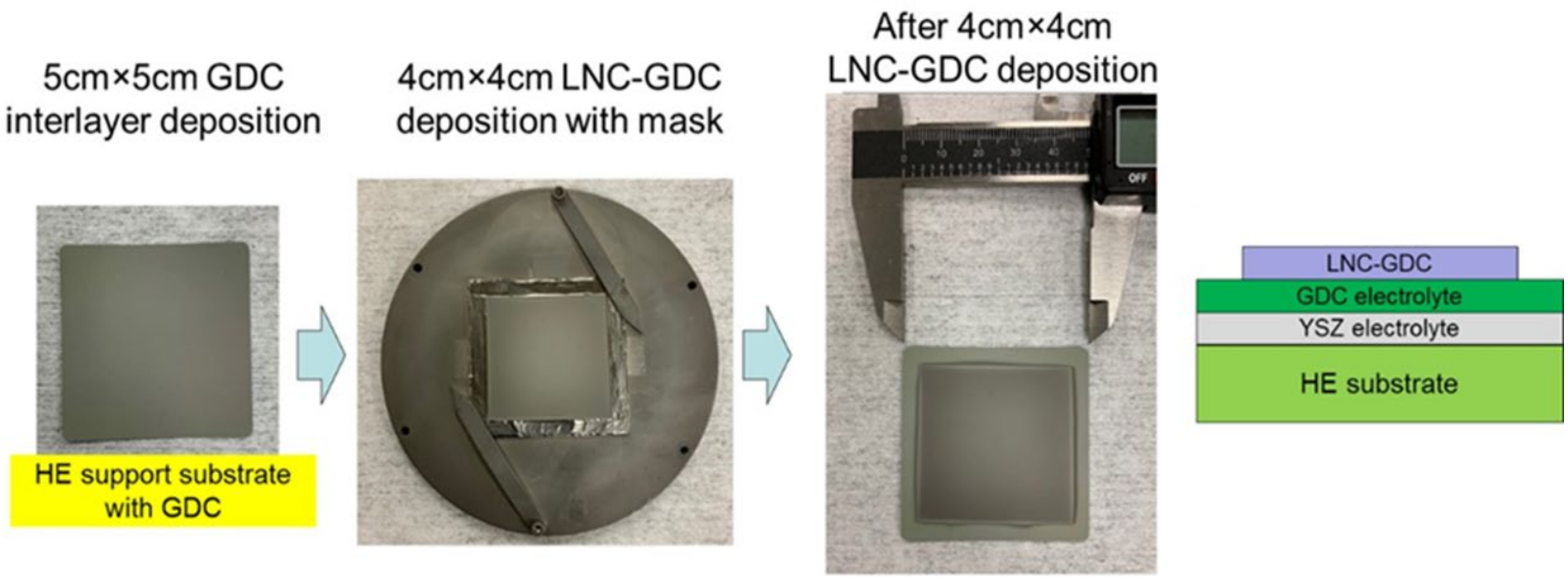
Scaleup Cell



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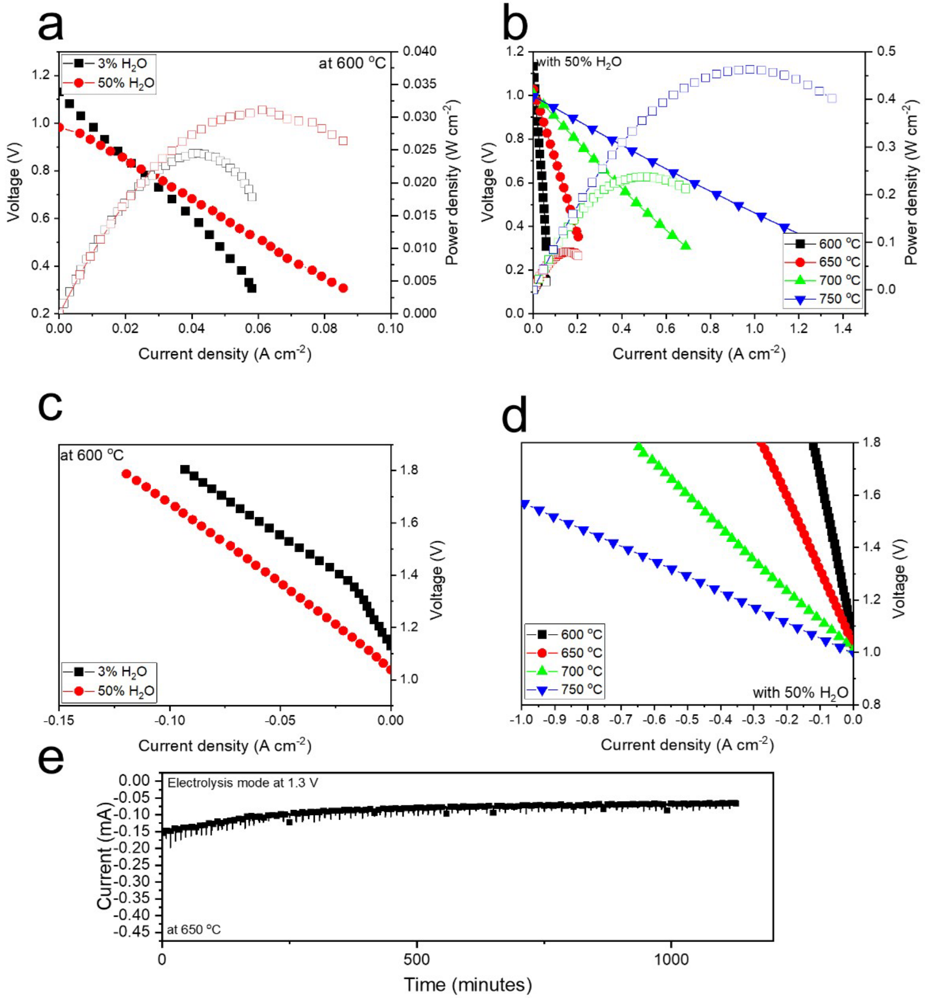
Evaluation of LNC-GDC Oxygen Electrode

- LNC-GDC electrode reversibility
- Performance better than conventional LSC-GDC electrode
- Short-term stability



Electrolyte support cell of configuration LNC-GDC|GDC|YSZ|Ni-YSZ

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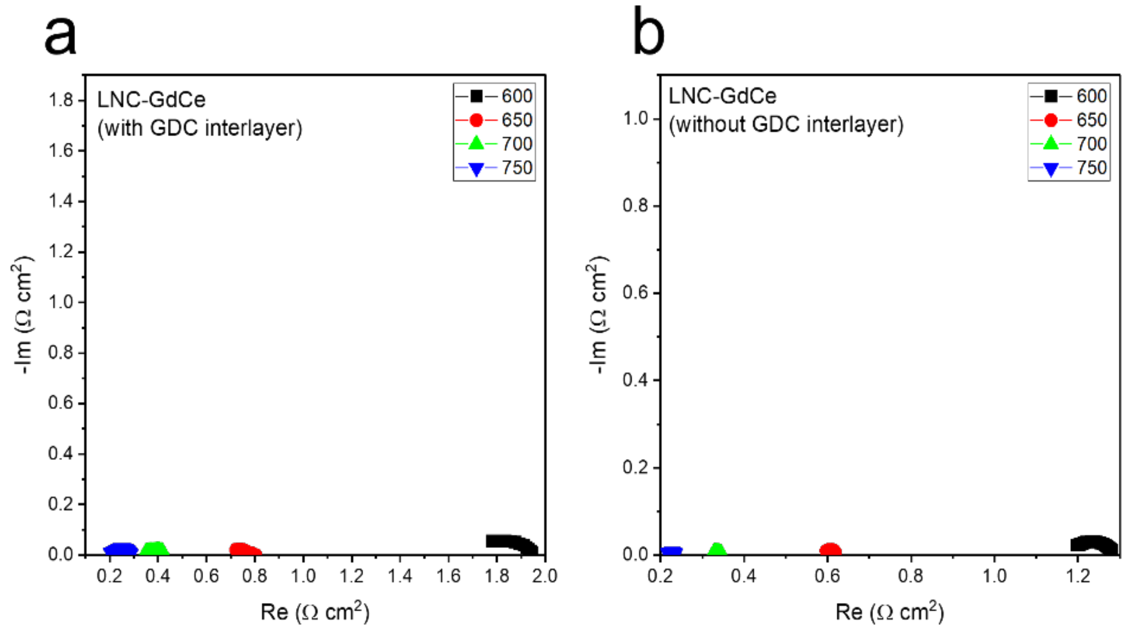
Evaluation of LNC-GDC Oxygen Electrode

with and without GDC interlayer

AC Impedance Spectra



YSZ supported symmetric cell with the configuration of
(a) LNC-GDC|GDC|YSZ|GDC|LNC-GDC and (b) LNC-GDC|YSZ|LNC-GDC

LNC-GDC electrodes without GDC interlayer showed better performance

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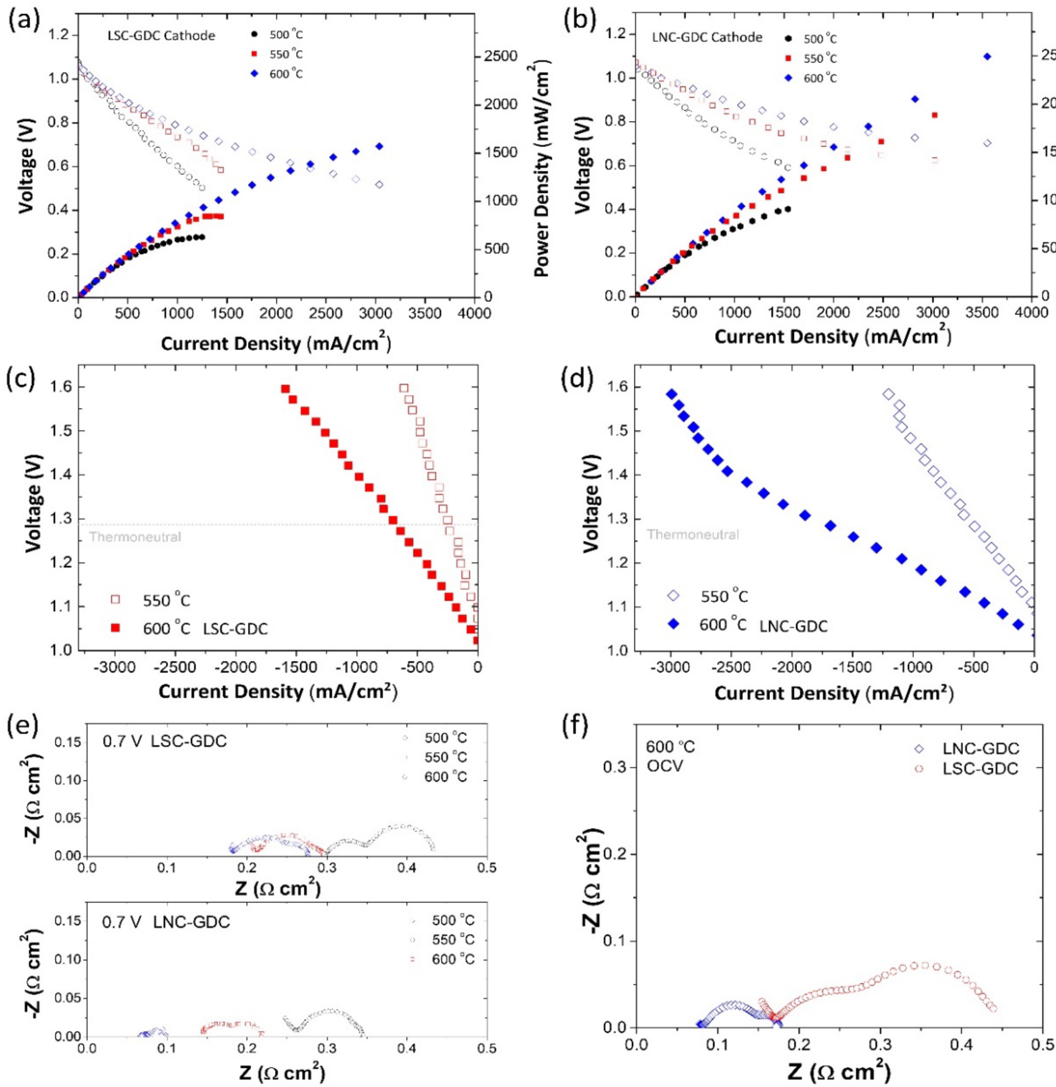
Sputtered Cell Performance

Comparison of LNC-GDC with LSC-GDC



Extraordinarily high cell performance with LNC-GDC oxygen electrode at reduced temperatures (550°-600°C)

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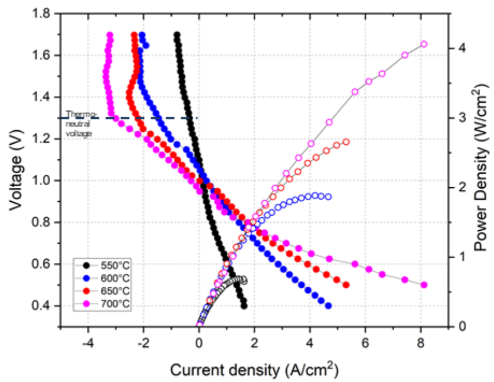
Cell Performance Mapping

Reversible Operation

by Temperature: 550, 600, 650, 700°C

- H_2O:H_2 50:50

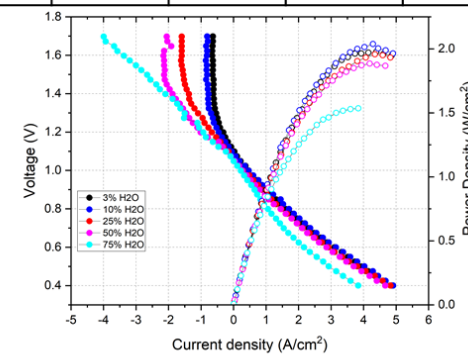
Temperature	550°C	600°C	650°C	700°C
OCV	1.11 V	1.06 V	1.03 V	0.96 V
Peak Power Density	0.69 W/cm^2	1.89 W/cm^2	2.66 W/cm^2	4.06 W/cm^2
Current Density at 1.3V	0.35 A/cm^2	1.45 A/cm2	2.21 A/cm^2	3 A/cm^2



by Steam Ratio: 3%, 10%, 25%, 50%, 75%

- Temperature: 600 °C

Steam Ratio	3%	10%	25%	50%	75%
OCV	1.10 V	1.09 V	1.07 V	1.06 V	1.04 V
Peak Power Density	1.98 W/cm^2	2.03 W/cm^2	1.96 W/cm^2	1.89 W/cm^2	1.54 W/cm^2
Current Density at 1.3V	0.55 A/cm^2	0.73 A/cm^2	1.13 A/cm^2	1.48 A/cm^2	1.51 A/cm^2

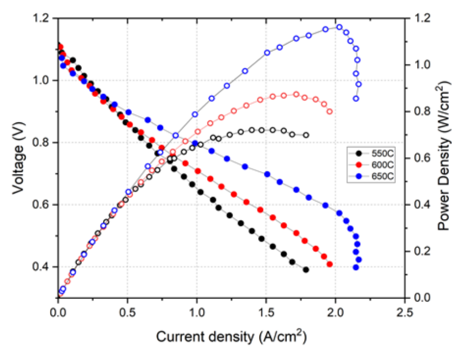


Fuel Cell Operation

CH_4 fueled: 550, 600, 650°C

- 3% H_2O

Temperature	550°C	600°C	650°C
OCV	1.12 V	1.11 V	1.07 V
Peak Power Density	0.72 W/cm^2	0.87 W/cm^2	1.16 W/cm^2



RSOC Stack Development

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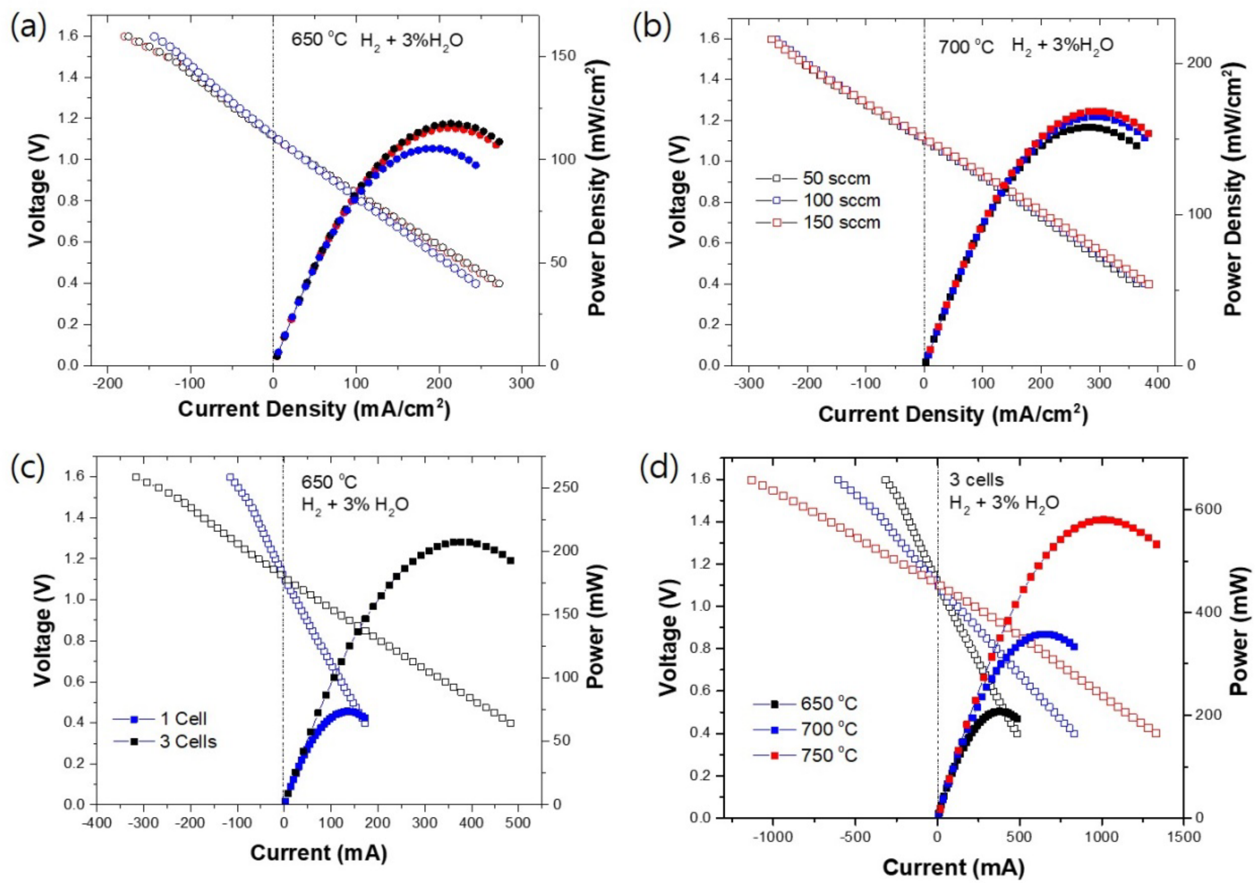
Testing of 3-Cell Stack



2cmx2cm electrolyte supported cells

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Highlights

Key accomplishments

- Demonstrated scalability of sputtering process
- Demonstrated superior cell performance with LNC-GDC oxygen electrode
- Showed feasibility of the stack architecture and potential for low stack cost
- Developed a metal coating process for porous AAO substrates
- Estimated stack capital cost and cost of hydrogen

DE-FE0032107

Project Overview

- Project: Development of 3D Cell Structure and Manufacturing Processes for Highly Efficient, Durable and Redox Resistant Solid Oxide Electrolysis Cells (DE-FE0032107)

- Project Objective: Develop and demonstrate highly efficient, durable and redox resistant solid oxide electrolysis cells (SOECs) with a focus on
  - (i) A cell design with the hydrogen electrode composed of two layers – a 3D hydrogen electrode support layer and an exsolved perovskite hydrogen electrode active layer
  - (ii) A manufacturing scheme incorporating advanced inkjet printing and photonic sintering for fabrication of the cell configuration

- DOE/NETL Project Manager: Ms. Sarah Michalik

- Project Team:
  - ❑ University of California San Diego (UCSD)
    - ▪ Nguyen Minh (PI)
  - ❑ RocCera
    - ▪ Sam Ghosh, Arkady Malakhov
  - ❑ Rochester Institute of Technology (RIT)
    - ▪ Denis Cormier
  - ❑ Oak Ridge National Laboratory (ORNL)
    - ▪ Edgar Lara-Curzio

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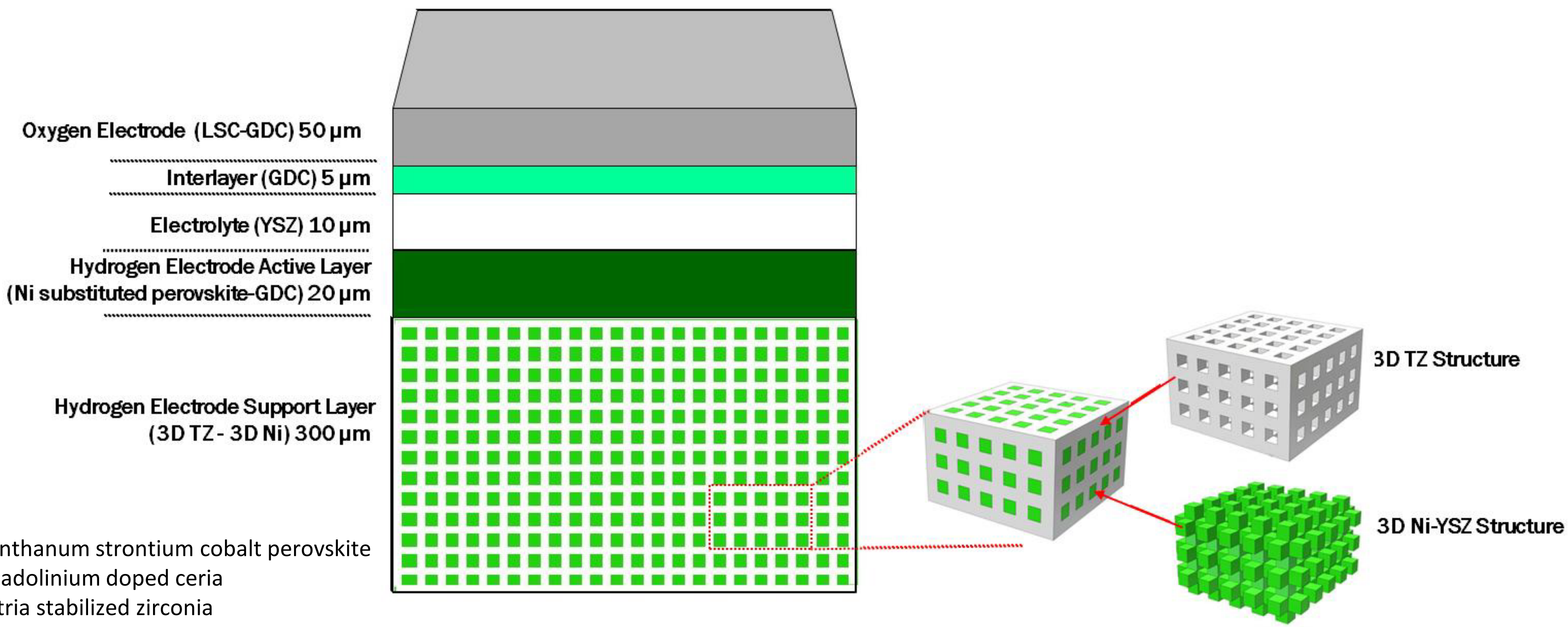
Cell Design

- Design features:
  - Hydrogen electrode supported configuration
  - Unique hydrogen electrode concept – a support layer with 3D structural geometry coupled with an exsolved perovskite active layer
- Motivation:
  - 3D hydrogen electrode support for redox resistance
  - Exsolved perovskite hydrogen electrode active layer (high performance, improved stability, redox resistance)



LSC: Lanthanum strontium cobalt perovskite
GDC: Gadolinium doped ceria
YSZ: Yttria stabilized zirconia
TZ: Tetragonal zirconia

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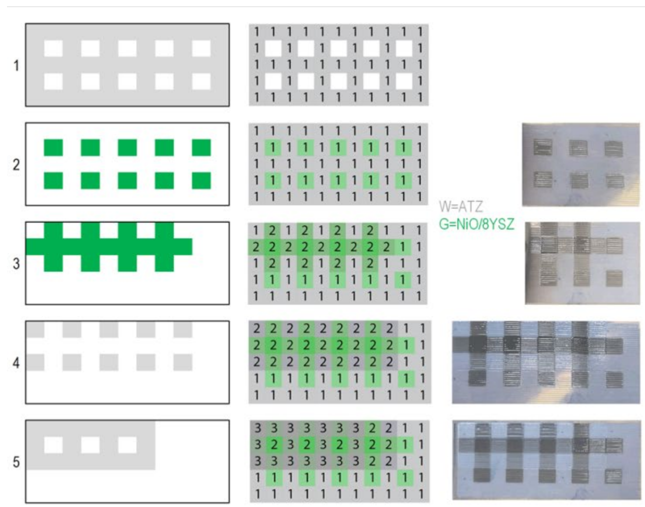
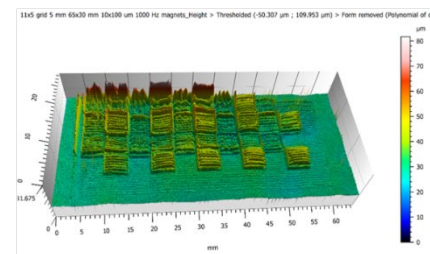
Inkjet Printing of Hydrogen Electrode Support

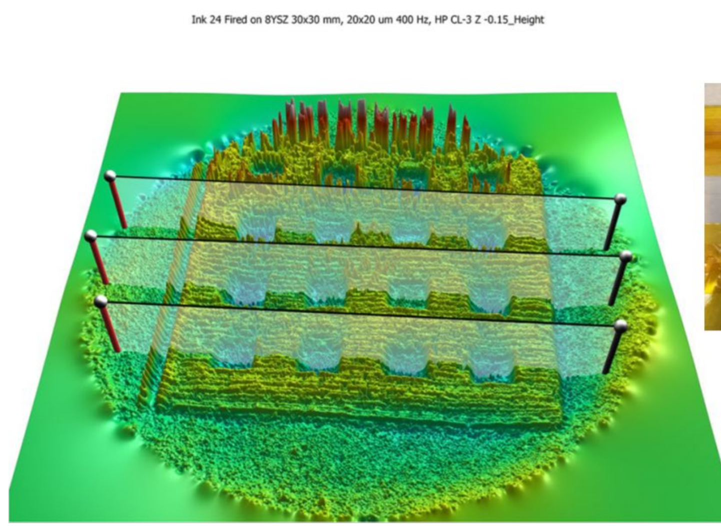
Printing

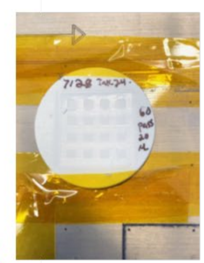


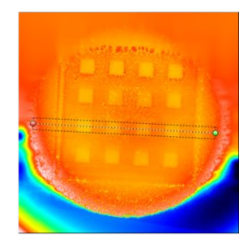
11	10	9	8	7	6	5	4	3	2	1
WWW	WGW	WWW	WGW	WWW	WGW	WWW	WG	WW	W	W
WGW	GG	WGW	GG	WGW	GG	WGW	GG	WG	G	W
WWW	WGW	WWW	WGW	WWW	WGW	WWW	WG	WW	W	W
W	G	W	G	W	G	W	G	W	G	W
W	W	W	W	W	W	W	W	W	W	W

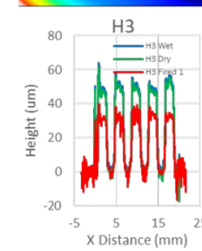


Firing









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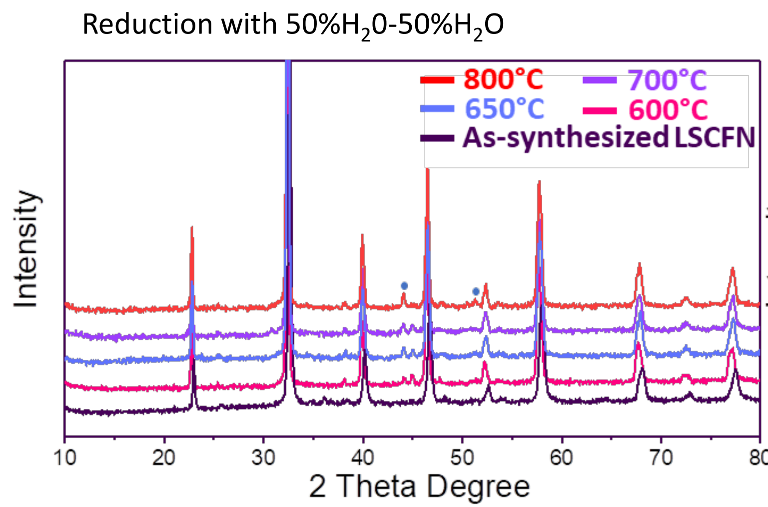
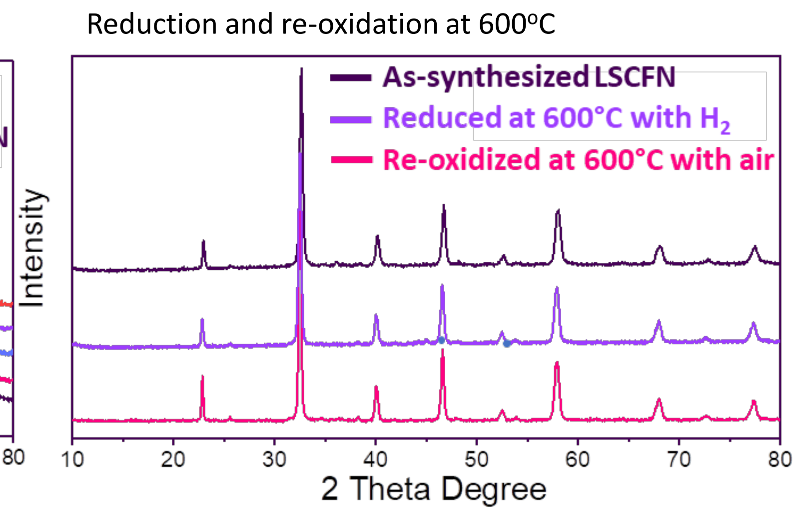
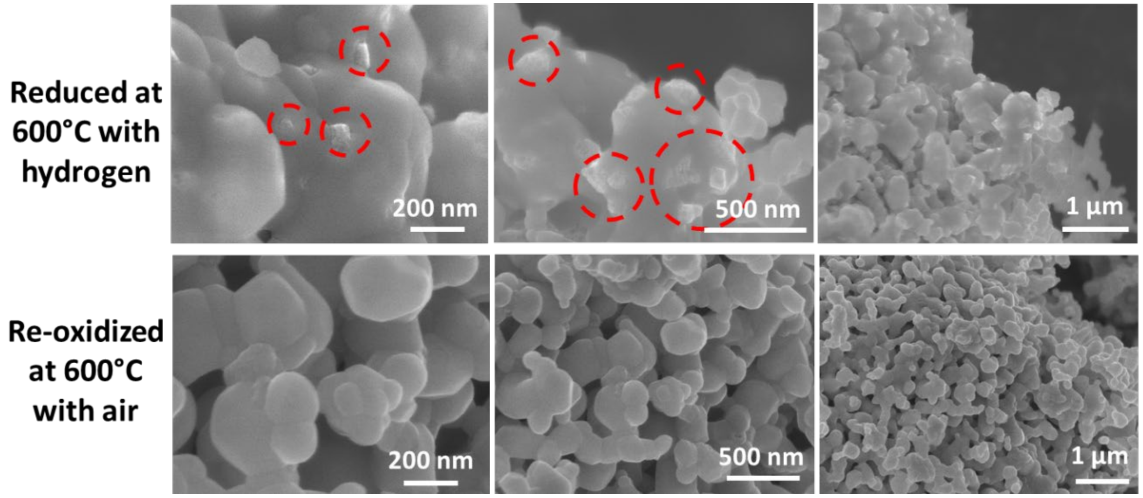
Nickel Exolution of Ni-Substituted Perovskite Hydrogen Electrode Active Layer







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Highlights

Key accomplishments

- Developed ink formulations
- Demonstrated inkjet printing of hydrogen electrode support configuration
- Demonstrated nickel exsolution in nickel substituted perovskite

Acknowledgments

- Ms. Sarah Michalik of DOE/NETL for assistance and support
- SOFC/SOEC/RSOC team at
  - UCSD and OxEon (31940)
  - UCSD, RocCera, RIT and ORNL (32107)