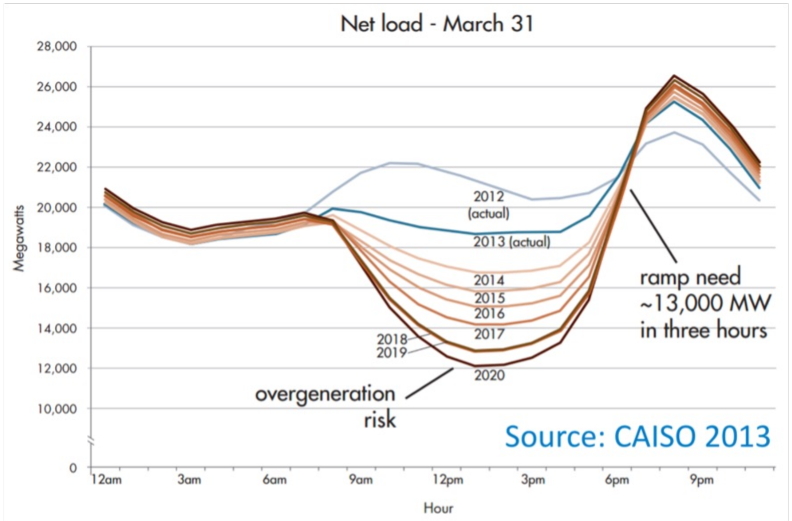
Reversible solid oxide cells for improving grid-scale renewable energy implementation

Jillian Rix Mulligan
IGS 2023 Summer Fellow
Advisor: Professor Soumendra Basu

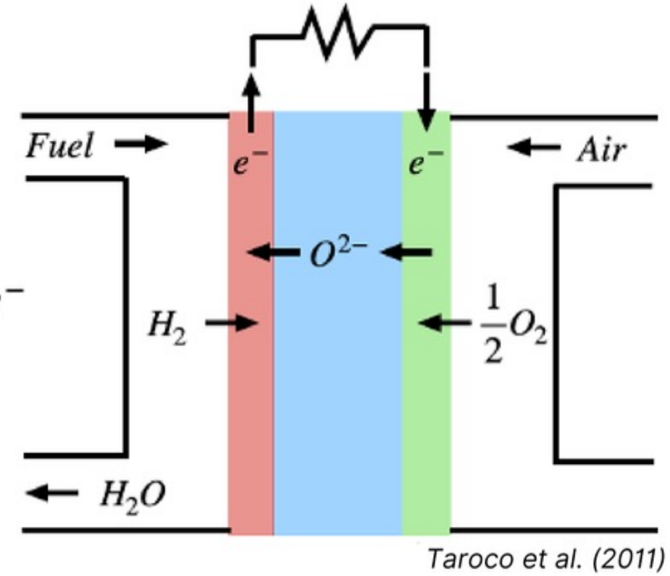
Boston University Institute for Global Sustainability
Division of Materials Science and Engineering

Reversible solid oxide cells



$$H_{2(g)} + \frac{1}{2}O_{2(g)} \leftarrow H_2O_{(g)}$$

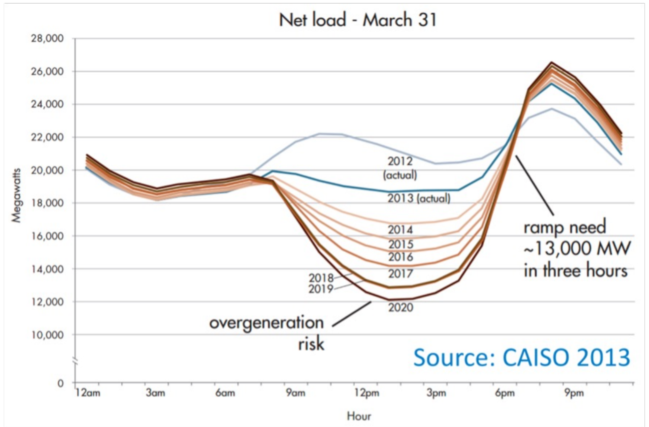
$$H_{2(g)} + O^{2-} \leftarrow H_2O_{(g)} + 2e^-$$

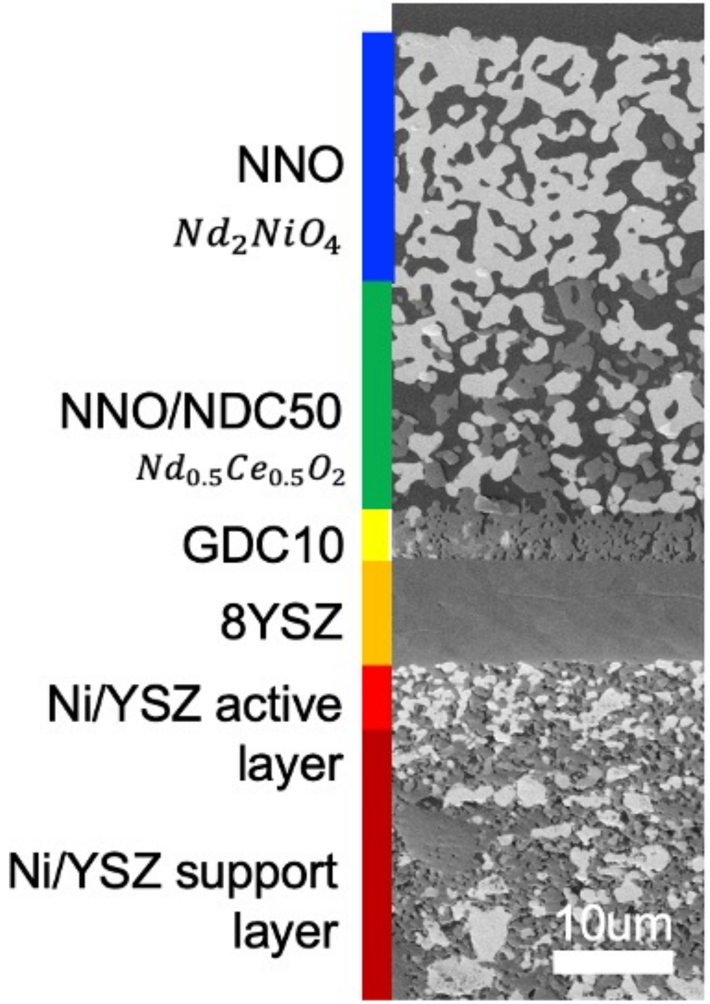


$$\frac{1}{2}O_{2(g)} + 2e^- \leftarrow O^{2-}$$

Project goals

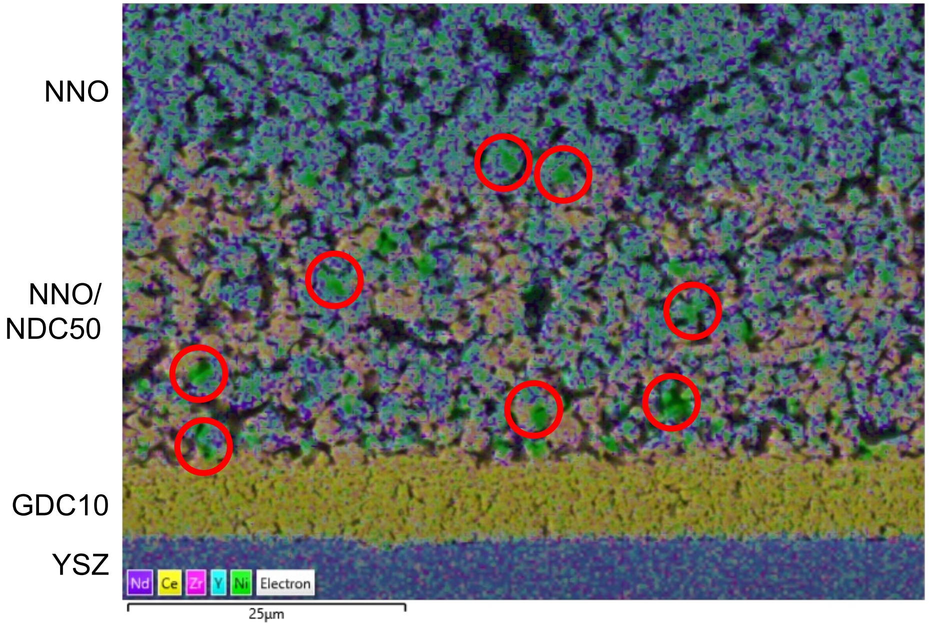
1. **Microstructure evolution during operation**
   - Characterizing cell microstructure and performance degradation
2. **Costs of RSOC implementation and scale-up**
   - Costs of novel electrode microstructures
   - Remaining obstacles to RSOC adoption



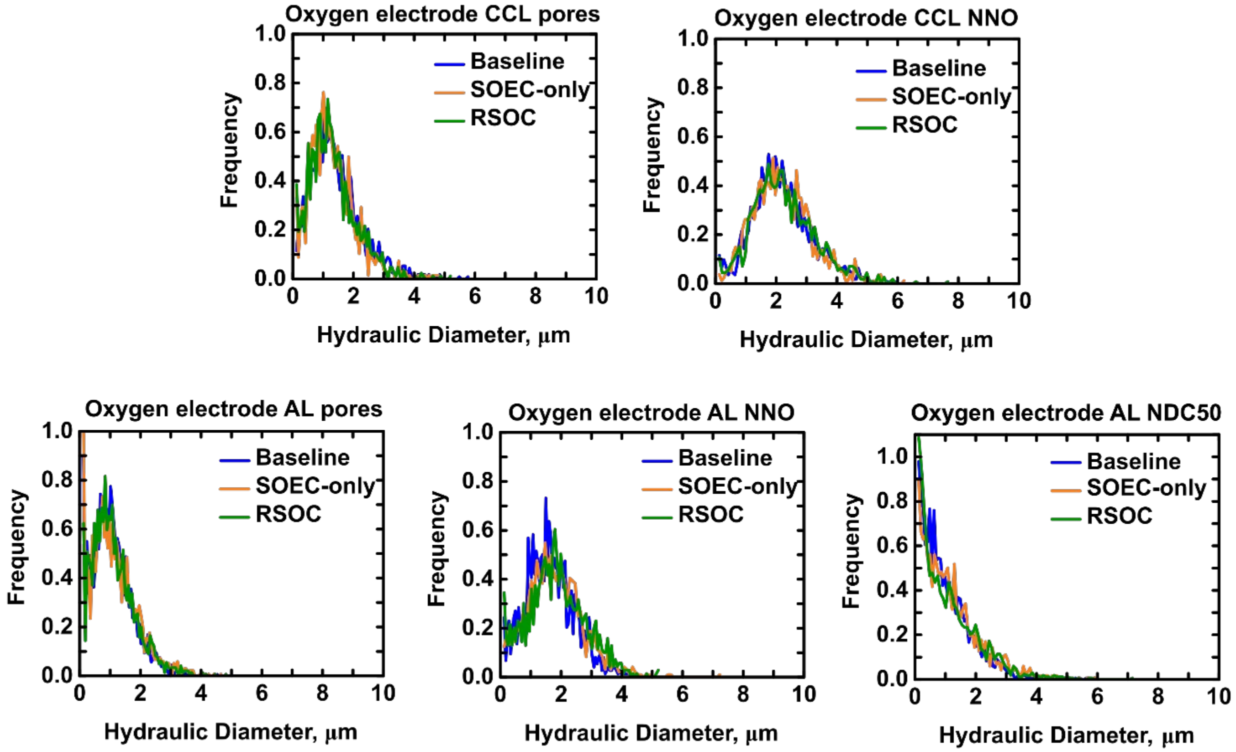


Microstructure evolution during operation

- **Oxygen electrode is stable over 500hrs of operation**



$$Nd_2NiO_4 \rightarrow Nd_2O_3 + NiO$$

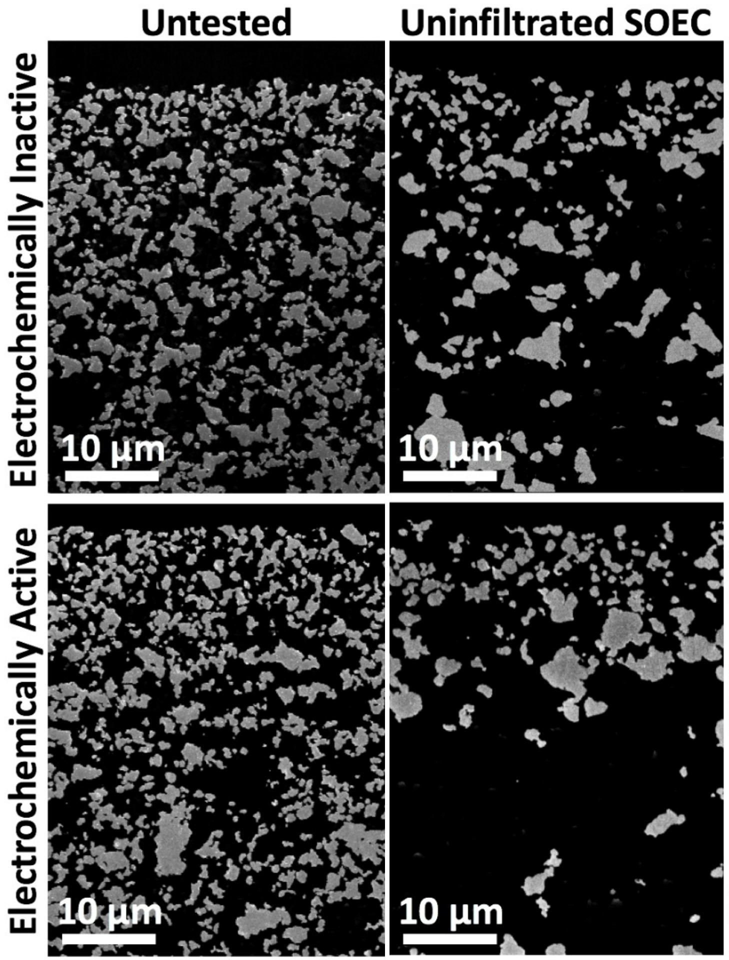


Microstructure evolution during operation

- Fuel electrode degradation occurs due to loss of active reaction sites
    1. Loss of connected Ni phase
    2. Coarsening of connected Ni phase

	Untested	Uninfiltrated SOEC
Change in connected Ni fraction (%)	-2.65	-23.15
Change in connected Ni particle size (%)	-2.22	20.77

- **GDC-infiltration mitigates both these degradation behaviors**



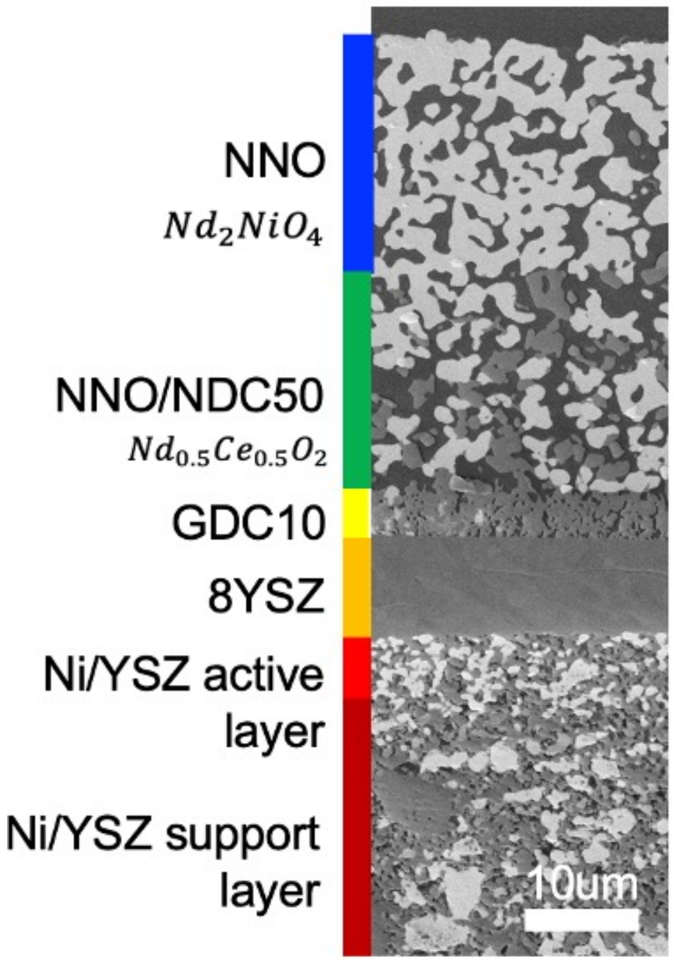
Images collected by Emily Ghosh

Costs of RSOC implementation and scale-up

- Compared energy costs of materials and processing for conventional and novel oxygen electrode

Oxygen electrode material	Total Energy Cost (MJ/Kg)	Electrolysis current density (Acm^{-2})	Fuel cell current density (Acm^{-2})
LSM-YSZ	235	0.085	0.1
LSCF-CGO	478	1.08	0.93
NNO-NDC50	446	1.67	1.31

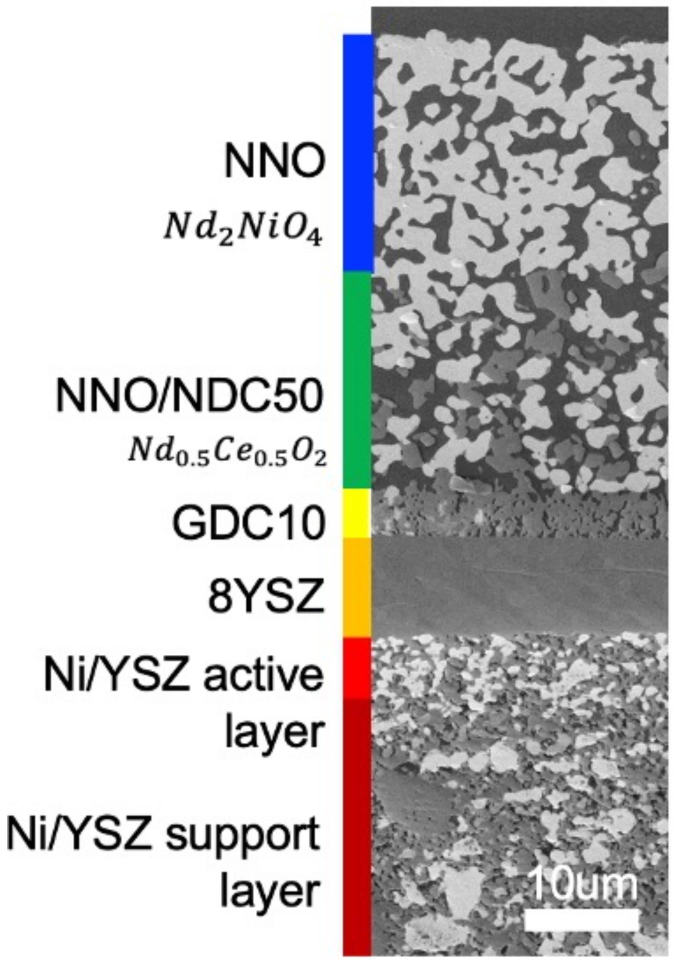
Database: Granta, Jung et al. (2016), Akter et al. (2022)



Costs of RSOC implementation and scale-up

Material	Critical list?	Abundance risk	Environmental country risk	Sourcing and geopolitical risk	Main sources
Gd	US and EU	Medium	Very high	Very high	China, US, Russia, India
Ce	US and EU	Medium	Very high	Very high	China, US, Russia
Ni	None	Medium	Very low	Very low	Australia, Russia, Canada, Indonesia, Philippines
Nd	US and EU	Medium	Very high	Very high	China, US, India
Sr	US and EU	Low	Medium	High	Spain, China
Co	US and EU	Medium	Low	Medium	Congo, Canada, China
Fe	None	Very low	Low	Low	China
La	US and EU	Medium	Very high	Very high	China, US, India
Mn	US	Low	Very low	Very low	Australia, Brazil, South Africa
Y	US and EU	Medium	Very high	Very high	China
Zr	US	Low	Very low	Very low	Australia, South Africa, China

Database: Granta



Costs of RSOC implementation and scale-up

Performance and efficiency

- Stability: current technologies have shown potential lifetimes up to 40,000h (Bosio 2023)
- Cost: Commercial targets require 80,000hr+ to be competitive (Bosio 2023)

Implementation

- Load following capability (Baldinelli 2019)
- High initial investment and public opinion (Salim 2022)
- Optimizing system management (Bianchi 2023)
- Thermal energy consumption and balance (Min 2022, Bianchi 2021)

Durability and system lifetime remains largest barrier

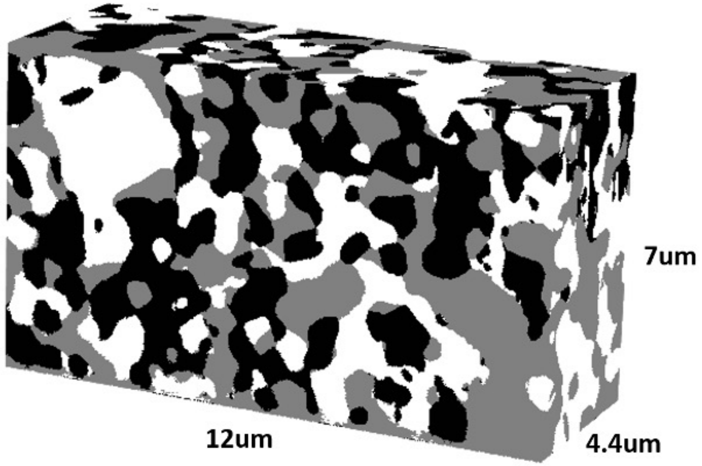
Future directions

Challenges

- Sample preparation and training on new instrumentation
- Long test times and large sample size requirements
- Accounting for lab-scale vs. industry scale production of electrodes

Future work

- 3D reconstruction characterization
- Continuing characterization with TEM
- Communicating and visualizing the challenges of renewable energy intermittency



Acknowledgements

Advisor: Prof. Soumendra Basu

Thesis committee: Prof. Uday Pal, Prof. Srikanth Gopalan, Prof. Emily Ryan

Research: Emily Ghosh, John-In Lee, Dr. Alexey Nikiforov

Support: Rebecca Pearl-Martinez, Prof. Benjamin Sovacool, Prof. Cutler Cleveland, Heather Clifford, Heather Quinlan-Baron, Roselourdes Deshon Mejia

Selected citations

A. Akter et al., Heavily Neodymium Doped Ceria as an Effective Barrier Layer in Solid Oxide Electrochemical Cells," International Journal of Hydrogen Energy (2022).

A. Baldinelli et al., "Progress in Renewable Power Exploitation: Reversible Solid Oxide Cells-Flywheel Hybrid Storage Systems to Enhance Flexibility in Micro-Grids Management," *Journal of Energy Storage* 23 (June 2019).\

A. Hauch et al., "Recent Advances in Solid Oxide Cell Technology for Electrolysis," Science 370, no. 6513 (October 9, 2020).

B. Bosio et al., "Multiscale Modelling Potentialities for Solid Oxide Fuel Cell Performance and Degradation Analysis," Sustainable Energy & Fuels 7, no. 1 (2023).

CASIO, "What the Duck Curve Tells us about Managing a Green Grid" (2013).

F. R. Bianchi et al., "Modelling and Optimal Management of Renewable Energy Communities Using Reversible Solid Oxide Cells," Applied Energy 334 (March 2023).

F. Rita et al., "Operating Principles, Performance and Technology Readiness Level of Reversible Solid Oxide Cells," Sustainability 13, no. 9 (April 24, 2021).

G. Min et al., "A Review of Solid Oxide Steam-Electrolysis Cell Systems: Thermodynamics and Thermal Integration," Applied Energy 328 (December 2022).

K. M. A. Salim et al., "Two Decades of Life Cycle Sustainability Assessment of Solid Oxide Fuel Cells (SOFCs): A Review," Sustainability 14, no. 19 (September 29, 2022).

S. H. Jensen et al., "Hydrogen and Synthetic Fuel Production from Renewable Energy Sources," *International Journal of Hydrogen Energy* 32, no. 15 (October 2007).