Highlights from the 2013 National Science Foundation Solid Oxide Fuel Cell Promise, Progress, and Priorities (SOFC-PPP) Workshop

by Jason D. Nicholas

Solid Oxide Fuel Cells (SOFCs) and Solid Oxide Electrolysis Cells (SOECs) (*i.e.*, SOFCs operated in reverse) are solid-state devices that can be used to (a) convert between chemical and electrical energy and/or (b) drive chemical reactions. These capabilities make them attractive for energy conversion, energy storage, chemical sensing, chemical separation, and chemical synthesis applications.

To articulate the unique benefits of these promising technologies and spur consensus on a successful SOFC/SOEC development path, leaders from academia, industry, the U.S. government, and the public policy community (identified in Table I) came together on July 11-12, 2013 for a National Science Foundation (NSF) sponsored Solid Oxide Fuel Cell Promise, Progress, and Priorities (SOFC-PPP) workshop. Highlights from the workshop are summarized here. Readers are referred to www.sofcwg.org for the full workshop report and whitepapers highlighting the unique benefits of these technologies for various constituencies.

Promise

Although SOFC/SOEC technology can be used for a variety of applications such as gas sensing, gas purification, *etc.*, the workshop participants agreed that the greatest promise for these devices lay in (1) using SOFCs for environmentally-friendly electricity generation, and (2) using SOECs for energy storage, carbon capture, and chemical synthesis.

SOFCs as a Clean and Efficient Path to a CO_2-Neutral Economy Powered by H_2, Biofuel, or Solar-fuels—SOFCs have many characteristics which make them attractive for producing electricity from fuels or energy-carriers (*i.e.*, chemicals that are used for "temporary" energy storage and are not viewed as energy sources in and of themselves). First, SOFCs have the highest theoretical and demonstrated efficiencies of any chemical to energy conversion technology: 50-60%$^{1-6}$ when electricity alone is valued, and 70-90%$^{4-6}$ when both electricity and high quality waste heat are valued. As shown in Fig 1., SOFCs also have some of the highest gravimetric and volumetric power densities of any electricity generation technology.[7] Unlike competing energy conversion technologies

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Table I. 2013 SOFC-PPP Workshop Participants.

Individual	Institution
Stuart Adler	University of Washington
Michele Anderson	Office of Naval Research
George Antos	National Science Foundation
Scott Barnett	Northwestern University
Noriko Behling	Freelance Author
Viola Birss	University of Calgary, Canada
Sean Bishop	Kyushu University, Japan
Zhe Cheng	Florida International University
William Chueh	Stanford University
Whitney Colella	Strategic Analysis, Inc.
Singaravelu Elangovan	Ceramatec, Inc.
Jeffrey Fergus	Auburn University
Gary Fischman	National Science Foundation
Hossein Ghezel-Ayagh	Fuel Cell Energy, Inc.
Raymond Gorte	University of Pennsylvania
Sossina Haile	Caltech
Michael Hill	Trans-Tech Inc.
Kevin Huang	University of South Carolina
Masaki Kawai	NGK Insulators
Cortney Kreller	Los Alamos National Laboratory
Burtrand Lee	Petroleum Research Fund
John Lemmon	Advanced Research Projects Agency-Energy
Daniel Lewis	Rensselaer Polytechnic Institute
Meilin Liu	Georgia Institute of Technology
Lynnette Madsen	National Science Foundation
Rodger McKain	LG Fuel Cell Systems U.S., Inc.
Nguyen Minh	The University of California at San Diego
Mohan Misra	ITN Energy Systems, Inc.
Mogens Mogensen	Technical University of Denmark, Riso
Daniel Mumm	University of California, Irvine
Yeshwanth Narendar	Saint-Gobain Ceramics and Plastics, Inc.
Jason Nicholas	Michigan State University
Eranda Nikolla	Wayne State University
Elizabeth Opila	University of Virginia
Nina Orlovskaya	University of Central Florida
Joshua Persky	Protonex Technology Corporation
Randy Petri	Versa Power, Inc.
Shriram Ramanathan	Harvard University
Jon Rice	Ultra Electronics AMI, Inc.
Kazunari Sasaki	Kyushu University, Japan
Justin Scott	The Minerals, Metals and Materials Society
Prabhakar Singh	University of Connecticut
Subhash Singhal	Pacific Northwest National Laboratory
Jacob Spendelow	Department of Energy Efficiency and Renewable Energy Program
S.K. Sundaram	Alfred University
Erik Svedberg	The National Academy of Sciences
Scott Swartz	NexTech Materials
Masaru Tsuchiya	Si Energy Systems, LLC
Anil Virkar	University of Utah
Eric Wachsman	University of Maryland
Mark Williams	URS Corp.
Bilge Yildiz	Massachusetts Institute of Technology

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such as gas turbines, SOFC efficiencies are size independent; making them effective for applications ranging from 1 Watt to multi-Megawatts. Examples of these applications include:

- 1 – 100W personal device power packs;
- 100W – 10kW uninterruptible power supplies;
- 2 – 5kW tractor trailer hotel load and/or refrigerated trailer auxiliary power units;
- 1 – 10kW unmanned aerial, ground, and underwater vehicles;
- 1 – 15kW natural gas pipeline metering stations, radar stations, cell-phone tower power units, and infrastructure support applications;
- 100W – 100kW distributed solar energy and smart grid energy storage applications;
- 20 – 40kW automotive hybrid units;
- 60 – 90kW automotive power plants;
- 1kW – 10MW residential, commercial, and industrial applications; and
- 100 – 500MW central power stations.

SOFCs also have the ability to utilize a variety of fuels and energy-carriers (hydrogen, ethanol, biofuel, gasoline, natural gas, syngas, landfill gas, jet-fuel, *etc*).[7,8] Debate currently exists on whether CO_2-free energy-carriers (such as hydrogen), or CO_2-neutral energy-carriers that uptake/release CO_2 when they are produced/consumed (such as bio- or solar-derived hydrocarbons) are best for use with renewable electricity generation. However, ~80% of annual world energy demand is projected to be met with hydrocarbon fuels for at least the next 30 years,[9] suggesting that R&D into the clean use of hydrocarbons should remain a world-wide priority. This is especially true for the United States, where new hydrocarbon recovery technologies (such as hydraulic fracturing) have lowered natural gas costs[10] and are projected to:

- make the U.S. the world's largest oil producer by 2017,[11]
- make the U.S. the world's largest natural gas exporter by 2020,[9] and
- make natural gas the most-used domestic fuel by 2030.[11]

This new era of cheap, domestically-produced natural gas is an opportunity to develop and deploy SOFCs and SOECs that can reduce the environmental impact of today's hydrocarbon based economy while simultaneously providing the infrastructure for a CO_2-neutral economy utilizing biofuels, solar fuels, or hydrogen.

SOFCs are beneficial in the near term because hydrocarbon-fueled SOFCs produce ~50% less CO_2, ~90% less NO_x, ~90% less SO_x, and virtually no particulates or volatile organic compounds, on a per Watt basis, compared to conventional hydrocarbon-fueled power plants.[12] In addition, SOFC anode exhaust streams can provide concentrated CO_2 for enhanced oil recovery or carbon sequestration. SOFCs are beneficial in the long term because the percent of renewably generated, CO_2-neutral H_2, biofuels, and/or solar-fuels used in centralized or distributed SOFC electricity generation facilities could be increased without the need for additional infrastructure.

SOFCs can be used in large-scale (*i.e.*, multi-megawatt) centralized power plants (where they benefit from \$/kW cost reductions),[13,14] or in distributed (*i.e.*, point-of-use) power generation units (where they are less vulnerable to attack and weather-related power-outages caused by damage to the above-ground electricity distribution network). In fact, the benefits of distributed SOFCs has already led companies such as Verizon Communications to install cell-phone tower SOFC units.[15] If SOFCs for distributed combined heat and power applications can be made economical, a huge market awaits in the 55% of the homes and businesses already connected to the U.S. natural gas distribution grid.[16]

SOECs for Energy Storage, Carbon Capture, and Chemical Synthesis.—SOECs have many characteristics which make them attractive for renewable (solar, wind, tidal, *etc.*) energy storage. First, SOECs have the highest fuel production to consumed electricity ratios of any electrical to chemical energy conversion technology, thanks to their reversible catalysts and their high operating temperatures.[17,18] Unlike batteries, SOEC electrodes remain inert during the energy storage process, allowing them to store as much energy as desired. Further, SOECs can store this energy in liquid hydrocarbons that have 2-5 times the gravimetric and volumetric energy densities of Li-ion batteries.[7,19] Alternatively, SOECs can store electrical energy by converting H_2O and/or CO_2 into H_2 and/or syngas ($CO + H_2$), and SOFC/SOEC combinations used for energy storage and conversion have modeled efficiencies of 60% (which is more than double those encountered today).[20]

SOECs can also be used to upgrade biomass energy sources, produce high energy density liquid transportation fuels (such as gasoline) for subsequent use in SOFCs, capture carbon in condensed phases, and produce designer chemicals. For instance, SOEC-produced syngas can be used in conventional processes to produce fuels, lubricants, fertilizers, plastics, adhesives, pharmaceuticals, synthetic

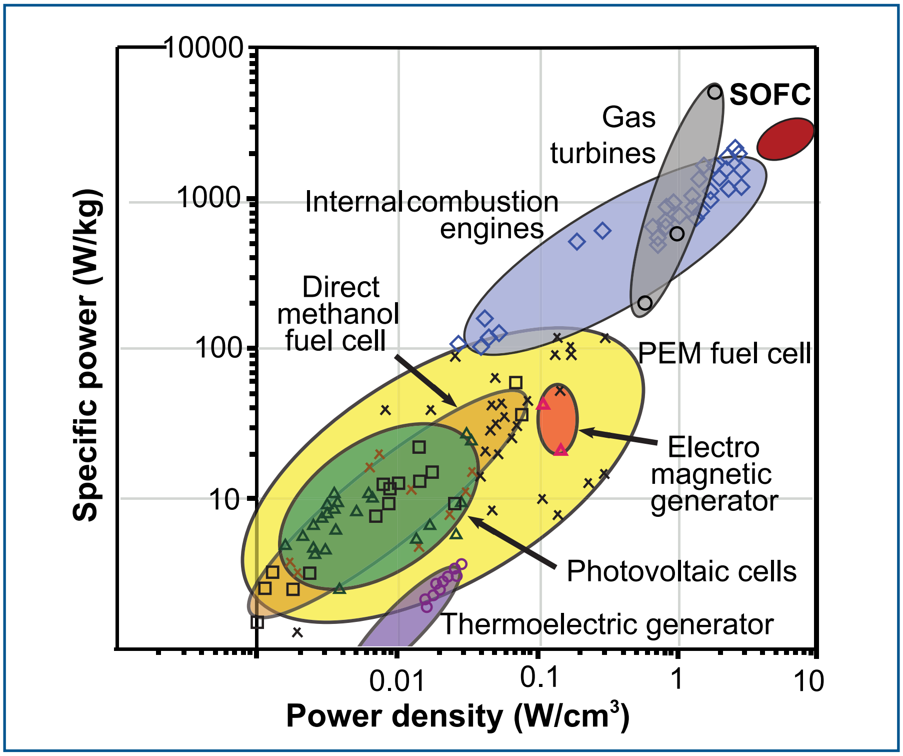


Fig. 1. *Gravimetric and volumetric power densities for various electricity generation technologies. Note that gas turbine efficiency scales with system size, and only large (~1 MW and greater) gas turbines exhibit specific powers greater than SOFCs. Also note that batteries have been excluded from this plot because they are an energy storage, not an electricity generation, technology. This figure was modified from Ref 7 with gas turbine data from Ref. 56 and 57. Reprinted with permission from AAAS with the condition that readers may view, browse, and/or download this figure for temporary copying purposes only, provided these uses are for noncommercial personal purposes. Except as provided by law, this material may not be further reproduced, distributed, transmitted, modified, adapted, performed, displayed, published, or sold in whole or in part, without prior written permission from the publisher.*

fabrics, and other hydrocarbons derivatives. Another intriguing possibility is to perform these chemical conversions directly within an SOEC with the aid of specially designed catalysts and the control over chemical driving forces, chemical reaction pathways, and reaction product selectivity that can be exerted by an electrical polarization.

Progress

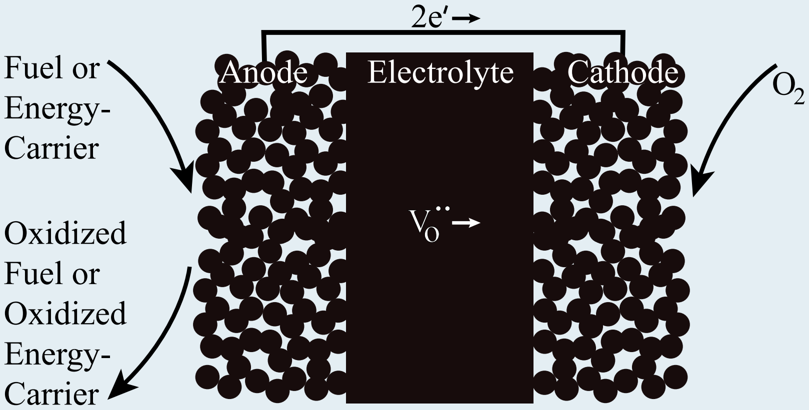
Over the past decade, the SOFC/SOEC community has achieved major advances in realizing the promise of these devices by reducing SOFC operating temperatures from ~1000°C to ~600°C,[7,8,21] demonstrating area-specific SOFC power densities in excess of $1W/cm^2$ above 600°C,[7,22] increasing SOFC lifetimes into the tens of thousands of hours range,[23] and reducing installed SOFC costs to the $6-8/Watt range.[13,14] (These costs are similar to those that were encountered by the solar industry a decade ago, and it is only now, with the help of the ~$300 million/year DOE Sun Shot program, that solar is starting to encounter widespread adoption as it moves from its current $3.50/Watt installed capacity price to an anticipated $1/ Watt cost by 2017.)[15,24] While installed costs of $4/W have been projected for scaled-up 100kW SOFC systems,[14] the SOFC-PPP workshop participants concluded that before SOFC/SOEC technology can move toward widespread practical application, progress on the critical scientific and engineering issues summarized in Table II must be made to reduce costs and/or improve device functionality, performance, and stability.

Priorities

Research and Development Priorities.—A list of critical scientific and engineering issues, an explanation why they are being researched, and recent developments impacting the need to, or likelihood of, solving these issues are summarized in Table II. Achieving progress on these issues was determined to be critical for placing SOFCs and SOECs on lower cost learning curve trajectories.

Policy Priorities.—The SOFC-PPP workshop participants agreed that U.S. SOFC funding of ~$100 million/year would be needed to make significant progress in solving the critical scientific and engineering issues summarized in Table II. This amount of funding could easily be offset by SOFC/SOEC efficiency-induced cost-savings in the $550 billion/year[9] energy business. Further, this amount of funding would place *per capita* U.S. SOFC R&D funding levels at $0.33/year, making them similar to the *per capita* commitments of other countries. Germany, for instance, funds SOFC R&D efforts at a *per capita* level of $1.50/year.[25,26] If U.S. SOFC funding levels were to be increased, several workshop participants expressed the opinion that a greater emphasis should be placed on fundamental research, compared to past efforts.

SOFC and SOEC Operating Principles



SOFCs are electrochemical mass and energy conversion and storage devices. Like all fuel cells, SOFCs utilize spatially separated redox reactions to drive ionic species through an electrolyte and electronic current through an external circuit. However unlike other types of fuel cells, SOFCs utilize solid-state materials with high oxygen vacancy ($V_O^{\bullet\bullet}$) conductivities and low interfacial oxygen exchange resistances. As shown above, this facilitates the transport of oxygen vacancies from the anode, where lattice oxygen (O_O^x) leaves the lattice to oxidize a fuel (or energy-carrier) and produce electrons (e') via the reaction:

$$Fuel\ (Energy\ Carrier)_{(g)} + (O_O^x)_{(s)} \rightarrow Oxidized\ Fuel(Energy\ Carrier)_{(g)} + V_{O\,(s)}^{\bullet\bullet} + 2e'_{(s)}$$

to the cathode, where oxygen vacancies and electrons are consumed as oxygen enters the lattice via the reaction:

$$V_{O\,(s)}^{\bullet\bullet} + 2e'_{(s)} + \tfrac{1}{2}O_{2(g)} \rightarrow (O_O^x)_{(s)}$$

Thus, as long as fuel/energy-carrier and oxidant are applied to the anode and cathode, respectively, electrons flow through the external circuit joining the anode and cathode (producing electricity). SOFCs purpose-built to operate in a reverse mode, where fuel (energy carrier) and oxidant are produced when oxidized fuel (energy carrier) and electricity are provided, are referred to as Solid Oxide Electrolysis Cells.

Workshop participants also suggested that greater efforts be made to educate the public, policy-makers, and the broader scientific community on the unique benefits of SOFCs, and to eliminate the misconception that all fuel cells have to be associated with the hydrogen economy. To this end, the development of widespread, highly visible SOFCs for niche applications (similar to the solar powered calculators of the 1970s or the current polymer electrolyte membrane-powered forklifts) was identified as a priority.

To support industry, it was also suggested that an unbiased, independent laboratory be set up to promote confidence in SOFC manufacturer performance claims.

Workshop participants also suggested that NSF and/or the Department of Energy (DOE) Basic Energy Sciences (DOE-BES) division consider whether the establishment of high-temperature electrochemistry programs aimed at bringing together ion transport, electro-catalysis, electrodics, nanostructures, and interfacial chemistry fuel cell/battery/chemical work together, would help advance their missions.

The workshop participants also called upon greater coordination between the various government agencies funding SOFC research and development. Opinions on the appropriate degree of coordination included:

- The creation of a National Fuel Cell Development Project (akin to the National Nanotechnology Initiative (NNI) and described more fully in Behling[27]) that would support basic research and product development activities on all fuel cell types and be led by a highly experienced manager with access to the nation's most senior leadership.
- The creation of a "Sun Shot" type program for fuel cells focusing on the most efficient use of currently available domestic hydrocarbon fuels. As was done for solar cells, this program would focus on overcoming barriers to commercialization with specific cost, efficiency, and durability goals, across all federal stakeholder agencies. It

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Table II. Critical SOFC/SOEC Scientific and Engineering Issues.

Research Area	Critical Scientific & Engineering Issues	What's New?
Expand SOFC/SOEC operating conditions by researching/developing:		
Stable, high-performance, low temperature SOFC materials	• Identifying the rate-limiting mechanisms for oxygen reduction, transport, and evolution • Exploring structures with new ionic conduction mechanisms • Developing new materials with higher ionic conductivity, lower oxygen surface exchange resistances, and higher catalytic activity	New oxygen and/or proton conducting materials, computational modeling, *in situ* testing capabilities, *etc.* [29-36]
Strain and/or interface engineered SOFC materials	• Understanding the relationship between performance, surface structure, stress/strain, catalytic activity, defect thermodynamics, defect kinetics, electronic structure, *etc.* under actual SOFC temperature, atmospheric, and electrochemical polarization conditions • Understanding how interface engineering can be used to alter materials properties and performance under SOFC operating conditions	Both strain[37] and interface effects[38-40] have recently been shown to enhance ionic transport and/or surface exchange kinetics.
Improved fuel flexible, high temperature anodes	• Understanding the activation of molecular structures and the impact of inorganic impurities when using fuels other than H_2 or CH_4 (such as direct carbon, biogas, JP-8, *etc.*) • Developing new materials and concepts for fuel flexible anodes • Developing techniques to recycle fuel in small scale systems • Eliminating costly external reforming by achieving internal reforming	The projected emergence of natural gas as the most-used domestic fuel by 2030[11] adds to the importance of this research area.
Anodes that catalyze CH_4 oxidation below 500°C	• Understanding and resolving chemical processes at catalytic time scales • Identifying materials that have fast oxygen exchange kinetics and catalyze CH_4 oxidation below 500°C	Much work has been done on methane oxidation heterogeneous catalysis under open-circuit conditions, but almost none has been done under polarized SOFC operating conditions.
Give SOFCs/SOECs new functionalities by researching/developing:		
Reversible SOFCs/SOECs for energy storage	• Understanding high overpotential effects on material performance and stability • Understanding pore formation in the electrolyte • Understanding delamination at oxygen electrode – electrolyte interfaces • Developing materials that are stable in both oxygen-rich and oxygen-deficient environments	SOECs are a new research area, with the number of papers increasing by 1500% over the past six years.[41]
SOFCs/SOECs for chemical synthesis	• Developing strategies for extracting value from the chemical conversion capability of SOFCs • Understanding high overpotential effects on catalysis performance, stability, and selectivity	
Improve SOFC/SOEC manufacturability by researching/developing:		
New processes for tailored microstructures	• Developing novel processes such as self-assembly, spinodal decomposition, multi-step infiltration, *etc.* to obtain new, desirable hierarchical microstructures • Developing interfacial mechanisms for increasing densification rate in low-cost processing • Understanding materials interactions and the effect on defects in co-processing • Leveraging domestic microelectronics expertise to produce micro-SOFCs • Developing materials that are easily scaled to manufacturing level processes and can be used with existing cell fabrication methods	The collaborative culture that has developed between academic and industrial members of the domestic SOFC community (as demonstrated by the participation of both groups in the SOFC-PPP workshop and the successful completion of joint DOE-SECA program projects), means that academic SOFC/SOEC advances can be quickly transferred to industry.

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would utilize a three-tiered, integrated-activity approach that would (1) build on the successes of both the DOE Solid State Energy Conversion Alliance (SECA) and DOE Energy Efficiency and Renewable Energy (EERE) Hydrogen and Fuel Cell programs, (2) utilize the DOE Advanced Research Projects Agency-Energy (ARPA-E) program to invest in new high-risk/high-reward material sets and technologies, and (3) expand the amount of fundamental fuel cell research funded by NSF and DOE-BES.

- Using groups like the Interagency Power Group (https://iapginfo.org/) to increase coordination between federal programs currently funding SOFC research.

Lastly, the workshop participants suggested that a National Academy of Sciences study be commissioned to aid policy-makers in how to best structure U.S. fuel cell policy and/or identify the best technologies (fuel cell or otherwise) for the clean utilization of hydrocarbon fuels in the context of a future U.S. energy mix with a variety of renewable energy sources.

Conclusions

As summarized in this report, SOFCs and SOECs offer a unique opportunity to reduce the environmental impact of today's hydrocarbon based economy while simultaneously providing the infrastructure for a CO_2-neutral economy utilizing biofuels, solar fuels or hydrogen. It is therefore alarming that U.S. SOFC programs, such as the DOE SECA program have been zeroed out in the DOE FY2012 and FY2013 budget requests.[28]

As members of the scientific community and our respective countries, we have the power to shape future SOFC/SOEC policy, and SOFC/SOEC policy has the power to shape our future. Both need our investment.

Disclaimer

The opinions expressed here are those of the academic, industrial, and public-policy SOFC-PPP workshop participants, and do not represent those of the National Science Foundation, the Department of Energy, the U.S. Government, or any other organization.

Acknowledgments

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Table II. Critical SOFC/SOEC Scientific and Engineering Issues. *(continued)*

Research Area	Critical Scientific & Engineering Issues	What's New?
Improve SOFC/SOEC performance and durability by researching/developing:		
Redox stable anodes	• Understanding the influence electronic and geometric structure have on catalytic activity • Understanding interfacial phase formation and segregation	New *in situ/in operando* techniques for studying behavior under SOFC operating conditions, *etc.*[36,42-44]
Sulfur tolerant anodes	• Understanding the sulfur poisoning mechanisms • Eliminating the need for an external desulfurizer by developing sulfur tolerant anodes	New computational modeling, *in situ* characterization techniques, strain engineering,[31,43] *etc.* The projected emergence of natural gas as the most-used domestic fuel by 2030[11] adds to the importance of this research area.
Cr-controlled metallic interconnects	• Understanding alloy oxidation mechanism to develop low electrical resistance protective scales • Identifying Cr-free alloys suitable for use in SOFCs • Developing Cr mitigation materials/solutions that allow low-cost steel interconnects	Recent advances in developing low temperature electrodes and electrolytes will mitigate these problems by allowing additional materials/coatings to be considered.
On-board diagnostics	• Developing on-board diagnostics that allow real-time efficiency, maximizing balance of plant adjustments to short-term load changes and long term cell degradation	This area remains largely unexplored, making it a rich area for advancement.
Thermo-mechano-chemical predictive capabilities	• Understanding and mitigating the effects that gradients in temperature, composition, and defect chemistry have on stress-strain deformation behavior and mechanical failure • Performing basic materials property (*i.e.*, elastic property, thermodynamic property, *etc.*) measurements to support SOFC commercialization efforts	Advances in high-throughput combinatorial materials science, and increased attention between mechanical, electrical, and chemical coupling in the SOFC community.[32,45-48]
Quantitative Performance/ Design Models	• Understanding microstructure-property-performance relationships in electrodes to link intrinsic thin film measurements to porous thick film electrode performance • Developing computational methods to predict phase equilibria • Developing atomic level computational methods sensitive to materials criticality to discover new materials with desirable electrochemical and catalytic properties • Developing predictive multi-physics simulations to link atomic processes to cell-level performance, and cell-level performance to stack-level performance • Developing better/new open-source economic-technology models to identify niche applications, and incorporate them into stack and reformer design models • Developing the tools, models, and designs necessary to reduce balance of plant (blowers, reformers, *etc.*) costs	Advances in nondestructive 3D microstructural reconstructions,[49-51] finite element/finite difference modeling of reconstructed SOFC geometries,[52,53] thermodynamic modeling of SOFC-relevant materials,[54] *etc.* With recent advances in stack technologies, balance of plant costs are the largest expense for large scale (*i.e.*, greater than ~15 kW) SOFC systems.[14]
Reliable degradation models	• Understanding the factors controlling microstructural (*e.g.*, nanoscale coarsening) and compositional (*e.g.*, Cr poisoning, surface segregation, *etc.*) degradation mechanisms • Connecting degradation to atomistic models, and validating these models in real systems to eliminate the gap between lab scale testing and real system degradation • Developing science-based accelerated testing protocols	Thin film materials degradation testing,[55] nondestructive 3D microstructural reconstructions,[49-51] computational modeling of surface evolution,[44] *etc.*

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About the Author

Jason Nicholas is an Assistant Professor in the Chemical Engineering and Materials Science Department at Michigan State University. His present research interests lie in utilizing the interplay between stress, microstructure, processing and materials properties to improve the performance of chemical-to-electrical energy conversion/storage devices (fuel cells, chemical separators, pseudo-capacitors, batteries, *etc.*) and environmentally-aware devices (electro-chromic coatings, chemical sensors, chemical actuators, *etc.*). Updates on his work can be found at https://www.egr.msu.edu/nicholasgroup/.

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