Sandia Report
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September 2019

Department of Energy Office of Electricity Energy Storage Peer Review 2019

GLOBAL PERSPECTIVE
OF ENERGY STORAGE

Hotel Andaluz
Albuquerque, New Mexico
September 23-26, 2019

2019

PARTNERSHIPS

ACADEMIA

University of Alaska
Many Traditions One Alaska

University of Arkansas

Clemson University

Michigan State University

University of Houston

University of Kentucky

NM State University

Northeastern University

The Ohio State University

South Dakota State University

SMU

The University of California Irvine
Fiat Lux
Let There Be Light

University of Washington

Texas
The University of Texas at Austin

The University of Tennessee Knoxville

Washington University in St. Louis

New Mexico Tech
Science • Engineering • Research University

SFCC
Santa Fe Community College

Davidson

The University of Utah

Stony Brook University

University of Texas Arlington

UNC Charlotte

CUNY
The City University of New York

INDUSTRY

Anza Electric Cooperative, Inc.
A Touchstone Energy Cooperative

Burlington Electric Department

Hawai'i Electric Light

EPRI Electric Power Research Institute

epb

NRECA America's Electric Cooperatives

ESA Energy Storage Association

EWEB

Green Mountain Power

CEC

GeneSiC Semiconductor

WattJoule

Urban Electric Power

Helix Power

Los Alamos — where discoveries are made

PNM

East Penn — ecoult energy storage solutions — Energy Storage Excellence

Creare

NAATBatt International

Mustang Prairie

UET UniEnergy Technologies

STATE PARTNERS

California Energy Commission

Connecticut Energy & Environment

NELHA

New Mexico emnrd — Energy, Minerals and Natural Resources Department

DOER Massachusetts Department of Energy Resources

STANDARD BODIES

IEC

IEEE Advancing Technology for Humanity

NFPA

FEDERAL PARTNERS

Bonneville Power Administration

United States of America Department of Energy

NHTSA National Highway Traffic Safety Administration

INTERNATIONAL

Energy Market Authority — Smart Energy, Sustainable Future

nite — National Institute of Technology and Evaluation

ELECTRICITY ADVISORY COMMITTEE MEMBERS

The mission of the Electricity Advisory Committee is to provide advice to the U.S. Department of Energy in implementing the Energy Policy Act of 2005, executing the Energy Independence and Security Act of 2007, and modernizing the nation's electricity delivery infrastructure.

John Adams
Electric Reliability Council of Texas

Christopher Ayers
NC Utilities Commission Public Staff

Tom Bialek
San Diego Gas & Electric Company

Laney Brown
AVANGRID

Paul Cicio
Industrial Energy Consumers of America

Armond Cohen
Clean Air Task Force

Robert Cummings
North American Electric Reliability Corporation

Ann Delenela
Ameren

Kimberly Denbow
American Gas Association

Andrew (Drew) Fellon
Trane Energy Supply Services

Flora Flygt
American Transmission Company (Ret.)

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Givens Consulting

Lisa Grow
Idaho Power

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The Grid Group LLC
Committee Chair

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General Infrastructure, LLC

Lola Infante
Edison Electric Institute

Mladen Kezunovic
Texas A&M University

Clay Koplin
Cordova Electric Cooperative

Arthur Kressner
Grid Connections, LLC

Charlotte Lane
West Virginia House of Delegates

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Tri-State Generation and Transmission

Jeff Morris
WA State House of Representatives

Richard S. Mroz
Resolute Strategies

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Florida Power and Light

Delia Patterson
American Public Power Association

Darlene Phillips
PJM Interconnection

Anda Ray
Electric Power Research Institute

Wanda Reder
Grid-X Partners, LLC
Committee Vice Chair

Pam Silberstein
National Rural Electric Cooperative Association

Ramteen Sioshansi
The Ohio State University

Marcos Valenzuela Ortíz
National Control Center for Energy in Mexico (CENACE)

David Wade
Electric Power Board of Chattanooga

Tom Weaver
American Electric Power

GLOBAL PERSPECTIVE
OF ENERGY STORAGE

U.S. DEPARTMENT OF
ENERGY

The Office of Electricity (OE) provides national leadership to ensure that the nation's energy delivery system is secure, resilient and reliable. OE works to develop new technologies to improve the infrastructure that brings electricity into homes, offices, and factories, and the federal and state electricity policies and programs that shape electricity system planning and market operations. OE also works to bolster the resiliency of the electric grid and assists with restoration when major energy supply interruptions occur.

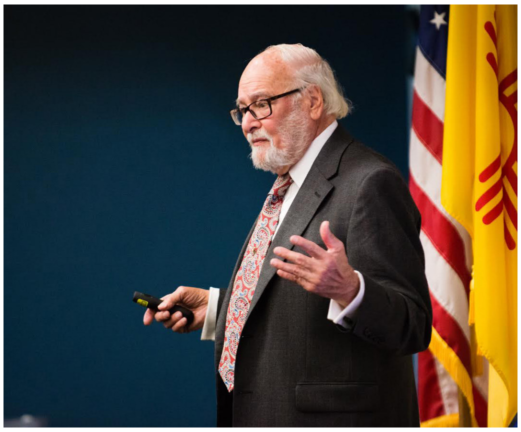
MISSION

OE drives electric grid modernization and resiliency in the energy infrastructure, leading the U.S. Deptment of Energy's (USDOE) efforts to ensure a resilient, reliable, and flexible electricity system. It accomplishes this mission through research, partnerships, facilitation, modeling and analytics, and emergency preparedness.

VISION

In OE's aspirations for the future, OE recognizes that our nation's sustained economic prosperity, quality of life, and global competitiveness depend on access to an abundance of secure, reliable, and affordable energy resources. Through a mix of technology and policy solutions, OE addresses the changing dynamics and uncertainties in which the electric system will operate. OE leverages effective partnerships, solid research, and best practices to address diverse interests in achieving economic, societal, and environmental objectives.

The United States Department of Energy (U.S. DOE) is pleased to welcome you to the annual Office of Electricity (OE) Energy Storage Program Peer Review.



At this event, a distinguished panel of experts will review and provide critical feedback on the DOE-funded projects at the national laboratories, academia, and industry partners. The criteria of the assessments are based on:

- **Completion of basic and applied research**
  - Project progress
  - Value of the results
  - Innovations
- **Appropriateness of approaches and methods**
  - Logic
  - Feasibility
  - Soundness of how proposed and executed research is conducted
- **Competency of research personnel**
  - Subject matter expertise
  - Performance of investigations
  - Teaming
- **Adequacy of resources**
  - Suitability of research environment
  - Facilities - Selection and Capabilities

The 2019 Department of Energy Office of Electricity (DOE OE) Energy Storage Program Annual Peer Review is the platform to present the results of projects funded by DOE OE completed over the last year. The work supports the OE priority of providing energy storage at the Mega-Watt scale. Three laboratories – Sandia National Laboratories, Pacific Northwest National Laboratory, and Oak Ridge National Laboratory – act as a collaborative to help establish the business case for energy storage as an emerging and enabling technology that supports the modernization of the grid to provide reliable, resilient, and responsible resources. This year there are at least 50 papers and 86 posters that tell the story of how the costs related to energy storage devices, related power electronics, materials, and systems can be reduced, and the value of storage systems increased in multiple benefit streams – both monetized and non-monetized. We are leading the way in research and development by overcoming obstacles to commercialization: safety, reliability, and development of environmentally benign battery resources. We are also meeting societal responsibilities related to re-use, recycling, and disposal of our materials, devices, and systems.

Please make the effort to network and exchange ideas as we move forward in our passion, our visions, and excellent work done in the national interest.

Dr. Imre Gyuk, Manager
Energy Storage Program
U.S. Department of Energy

DOE/OE ENERGY STORAGE PROGRAM'S NATIONAL LABORATORIES COLLABORATIVE

SANDIA NATIONAL LABORATORIES

For more than 60 years, Sandia has delivered essential science and technology to resolve the nation's most challenging security issues. Sandia National Laboratories is a multi-mission laboratory managed and operated by the National Technology & Engineering Solutions of Sandia, LCC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Agency (NNSA) and supports numerous federal, state, and local government agencies, companies, and organizations. As a Federally Funded Research and Development Center (FFRDC), Sandia may perform work for industry, responding to certain types of federal government solicitations.

A strong science, technology, and engineering foundation enables Sandia's mission of national security through a capable research staff working at the forefront of innovation, collaborative research with universities and companies, and discretionary research projects with significant potential impact. Sandia's employees are recognized by their professional peers for their outstanding contributions.

Although most of Sandia's approximately 10,000 employees work at Sandia's headquarters in Albuquerque, New Mexico, or at its second principal laboratory in Livermore, California, others are working at various sites in the U.S. and abroad to deliver innovative and reliable solutions in a changing world.

PACIFIC NORTHWEST NATIONAL LABORATORY

Discovery in action. These words describe what we do at PNNL, which has been operated by Battelle and its predecessors since our inception in 1965. For more than 50 years, we've advanced the frontiers of science and engineering in the service of our nation and the world. We make fundamental scientific discoveries that illuminate the mysteries of our planet and the universe. We apply our scientific expertise to tackle some of the most challenging problems in energy, the environment, and national security.

Research is our business. With an unwavering focus on our missions, scientists, and engineers at PNNL deliver science and technology. We conduct basic research that advances the frontiers of science. We translate discoveries into tools and technologies in science, energy, the environment and national security.

For more than four decades, our experts have teamed with government, industry, and academia to tackle some of the toughest problems facing our nation. The result: We're delivering the science, technology, and leadership our customers need to succeed.

OAK RIDGE NATIONAL LABORATORY

The Oak Ridge National Laboratory (ORNL) is the nation's largest multi-program science and technology laboratory. ORNL's mission is to deliver scientific discoveries and technical breakthroughs that will accelerate the development and deployment of solutions in clean energy and global security. Today, ORNL pioneers the development of new energy sources, technologies, and materials and the advancement of knowledge in the biological, chemical, computational, engineering, environmental, physical, and social sciences.

Originally known as Clinton Laboratories, ORNL was established in 1943 to carry out a single, well-defined mission: the pilot-scale production and separation of plutonium for the World War II Manhattan Project. The laboratory was also highly involved in isotope research and production. From this foundation, ORNL has evolved into a unique resource for addressing important national and global energy and environmental issues.

The EM program has numerous missions and responsibilities at the ORNL campus, and our employees are focused on removing past legacies and improving environmental health and employee safety—allowing modernization of one of DOE's greatest assets. The main ORNL site occupies approximately 4,470 acres and includes facilities in two valleys: Bethel Valley and Melton Valley.

GLOBAL PERSPECTIVE OF ENERGY STORAGE

Hotel Andaluz in Albuquerque, New Mexico September 23-26, 2019

DAILY AGENDAS

2:00 PM	**3:00 PM**	**Early Registration Begins**
3:00 PM	**4:00 PM**	**Postdoctoral Poster Set-Up**
4:00 PM	**5:00 PM**	**Peer Reviewer Orientation**

POSTDOCTORAL POSTER SESSION

5:00 PM - 6:00 PM	Energy Storage Planning Efforts for Regional Demonstrations Projects	Alexander Headley, Sandia National Laboratories Tu Nguyen (PI)
	Energy Storage Valuation at San Carlos Apache Tribe	Rodrigo Trevizan, Sandia National Laboratories Ty Nguyen (PI)
	Zincate-Blocking Polymeric Separators for Zn/MnO2 Batteries	Igor Kolesnichenko, Sandia National Laboratories Tim Lambert (PI)
	Interfacial Engineering in Sodium Batteries	Martha Gross, Sandia National Laboratories Erik Spoerke (PI)
	Effect of ZnO-Saturated Electrolyte on Rechargeable Alkaline Zinc Batteries at High Depth-of-Discharge	Matthew Lim, Sandia National Laboratories Tim Lambert (PI)
	Synthesis of Advanced Magnetic Materials for Inductors and Transformers	Tyler Stevens, Sandia National Laboratories Todd Monson (PI)
	Advanced Cathodes for Intermediate-Temperature Na-Metal Halide Batteries	Xiaowen Zhan, Pacific Northwest National Laboratory Guosheng Li (PI)
	Reliability Testing of Lead Acid Battery Module for grid services	Nimat Shamim, Pacific Northwest National Laboratory David Reed (PI)
	Dihydroxyphenazines as Anolytes for Aqueous Redox Flow Batteries	Nadeesha Nambukara Wellala, Pacific Northwest National Laboratory
	Operando Investigations of Bismuth Additives on the Rechargeability of MnO2 in Alkaline Batteries	Andrea Bruck, Northeastern University Matthew Kim, Northeastern University Josh Gallaway (PI)

6:00 PM	**7:00 PM**	**Meet & Greet Reception**

7:00 AM	**8:00 AM**	**Breakfast**	
8:00 AM	**9:00 AM**	**Opening Plenary / Day 1 Overview** **DOE Welcome**	Jim Greenberger, NAATBatt Dr. Imre Gyuk, DOE Office of Electricity
		PARTNERSHIPS	
9:00 AM	**10:00 AM**	2020 Biennial Energy Storage Review	Ramteen Sioshansi, The Ohio State University
		Engaging Academia: Creating Productive Networks	Erik Spoerke, Sandia National Laboratories
		Update on Energy Storage System Reliability Codes & Standards Activities	Charlie Vartanian, Pacific Northwest National Laboratory
		Energy Storage Projects Team Overview	Daniel Borneo, Sandia National Laboratories
10:00 AM	**10:15 AM**	**BREAK**	
		EQUITABLE REGULATORY ENVIRONMENT	
10:15 AM	**11:30 AM**	Overview of Equitable Regulatory Environment Programs at PNNL	Jeremy Twitchell, Pacific Northwest National Laboratory
		Regulatory Insights from the Southeastern Energy Storage Workshop	Rebecca O'Neil, Pacific Northwest National Laboratory
		An Energy Storage Valuation Handbook for Regulators	Dhruv Bhatnagar, Pacific Northwest National Laboratory
		Valuation of Energy Storage in the US Electricity and Frequency Regulation Markets	Felipe Wilches-Bernal, Sandia National Laboratories
		Energy Storage Policy Initiatives	Will McNamara, Sandia National Laboratories
		INDUSTRY ACCEPTANCE	
11:30 AM	**12:45 PM**	Nantucket Island Energy Storage System Assessment	Patrick Balducci, Pacific Northwest National Laboratory
		Demonstration of Energy Storage Benefits Around the Nation	Ben Schenkman, Sandia National Laboratories
		Microgrid Evaluation Tool	Di Wu, Pacific Northwest National Laboratory
		Technical Challenges for Energy Storage in Metro Rail Applications	Kevin Blackman, Helix Power Corporation
		BESS Control of A Grid to Liberate Renewables	Clay Koplin, Cordova Electric Cooperative (CEC)

TUESDAY, 24 SEPTEMBER 2019

12:45 PM - 1:45 PM		**LUNCH**	
MATERIALS I			
1:45 PM	**3:00 PM**	Zn/MnO2 Batteries	Tim Lambert, Sandia National Laboratories
		Progress on the development of the Zn-MnO2 rechargeable battery	Sanjoy Banerjee, Urban Electric Power
		High Voltage Zn-MnO2 batteries: Making Zn the new Li	Gautam Yadav, City College of New York
		Discharge Mechanism of MnO2 in Deep-Cycle Rechargeable Zn/MnO2 Batteries	Igor Vasiliev, New Mexico State University
		Advanced Manganese Oxide-based Cathodes for Rechargeable Aqueous Zinc-ion Batteries	Xingbo Liu, Pacific Northwest National Laboratory
3:00 PM	**3:15 PM**	**BREAK**	
SAFETY PERFORMANCE			
3:15 PM	**4:15 PM**	Thermal Runaway Risks for Li-ion Batteries in Energy Storage Systems	Hsin Wang, Oak Ridge National Laboratories
		Abuse Test Development: Mechanisms and Materials Impact of Abused Lithium-Ion Batteries	Loraine Torres-Castro, Sandia National Laboratories
		Predicting and Mitigating Cascading Failure in Stacks of Lithium-Ion Cells	John Hewson, Sandia National Laboratories
		Update on Energy Storage System Safety Codes & Standards Activities	Matthew Paiss, Pacific Northwest National Laboratory
POSTER SESSION I			
4:30 PM	**6:00 PM**	Reliability Analytics Analytics Materials II Power Electronics	

7:00 AM	**8:00 AM**	**Breakfast**	
8:00 AM	**8:15 AM**	**Plenary Review & Overview**	Jim Greenberger, NAATBatt
RELIABILITY			
8:15 AM	**9:30 AM**	Long-term Performance Assessment of Li-ion Battery Chemistries under Grid Services	Daiwon Choi, Pacific Northwest National Laboratory
		Safety and Performance of Commercial Lithium-Ion Cells	Yuliya Preger, Sandia National Laboratories
		Heat Release from Thermal Decomposition of Layered Metal Oxide Cathodes in Lithium-Ion Batteries	Randy Shurtz, Sandia National Laboratories
		Battery State of Health Model	Vish Viswanathan, Pacific Northwest National Laboratory
		Washington Clean Energy Fund Battery Testing Program Results	Alasdair Crawford, Pacific Northwest National Laboratory
9:30 AM	**9:45 AM**	**BREAK**	
ANALYTICS			
9:45 AM	**11:00AM**	Overview of Sandia's Energy Storage Analytics Work/Equitable Regulatory Environment Thrust Area	Raymond Byrne, Sandia National Laboratories
		Operating Cost Model for Battery Energy Storage System	Tu Nguyen, Sandia National Laboratories
		Energy Storage Financing & System Pricing Survey Study Series	Richard Baxter, Mustang Prairie Energy
		Optimization Performance Evaluation Tool	Jan Alam, Pacific Northwest National Laboratory
		QuESt: An Energy Storage Application Suite	Ricky Concepcion, Sandia National Laboratories

MATERIALS II			
10:45 AM	12:15 PM	Elucidating Molecular Transport through Membranes in Flow Batteries	Travis Anderson, Sandia National Laboratories
		Materials and Membranes for High Energy Density Non-Aqueous Redox Flow Batteries	Jagjit Nanda, Oak Ridge National Laboratory
		Phenazine-Based Anolyte Materials in Aqueous Redox Flow Batteries	Aaron Hollas, Pacific Northwest National Laboratory
		Capacity fade with aqueous-soluble organics: its measurement, minimization, and reversal	Michael Aziz, Pacific Northwest National Laboratory
		Predicting functionality and resiliency of aqueous organic redox flow battery	Vijay Murugesan, Pacific Northwest National Laboratory
12:30 PM - 1:30 PM		LUNCH	

MATERIALS II (CONTINUES)			
1:30 PM	3:15 PM	Low Temperature Molten Sodium Halide Batteries	Erik Spoerke, Sandia National Laboratories
		Component Research for Redox Flow Batteries and Open Batteries	Tom Zawodzinski, Oak Ridge National Laboratory
		Battery Systems Based on Naturally Abundant, Low Cost Materials	Amy Marschilok, Stony Brook University Esther Takeuchi, Stony Brook University Kenneth Takeuchi, Stony Brook University
		Advanced Membranes for Flow Batteries: Anion Exchange Membranes	Cy Fujimoto, Sandia National Laboratories
		Understanding the Mechanical Behavior of Materials for Electrochemical Energy Storage	Yang-Tse Cheng, University of Kentucky

MATERIALS II (CONTINUES)			
1:30 PM	**3:15 PM**	Investigation of Intermediate-Temperature Na-Metal Halide (Na-MH) Batteries and Large Cell Demonstration	Guosheng Li, Pacific Northwest National Laboratory
		Development of high-performance Na-ion battery with layered transitional metal oxide cathodes	Xiaolin Li, Pacific Northwest National Laboratory
3:15 PM - 3:30 PM		**BREAK**	
POWER ELECTRONICS			
3:30 PM	**4:45 PM**	Development of the Sandia Advanced Power Electronic Conversion Systems Laboratory	Jacob Mueller, Sandia National Laboratories
		Smart GaN-based Inverters for Grid-tied Energy Storage Systems	Medhi Ferdowsi, InnoCit
		Low Voltage and High Current Bidirectional Converter for Grid-tied Flow Battery Energy Storage System	Alex Huang, University of Texas at Austin
		High Frequency Link Converters using Advanced Magnetics	Todd Monson, Sandia National Laboratories
		Medium-voltage Power Electronics for Grid-tied Energy Storage	Anant Argawal, The Ohio State University
POSTER SESSION II			
4:45 PM	**6:15 PM**	Partnerships: Academia, Industry, Professional Organizations, Standards Boards Equitable Regulatory Environment Industry Acceptance Materials I Safety Performance	

THURSDAY, 26 SEPTEMBER 2019

7:00 AM	8:45 AM	**Breakfast**	
8:45 AM	9:00 AM	**Plenary Review**	Jim Greenberger, NAATBatt
ENERGY STORAGE EQUITABLE REGULATORY ENVIRONMENT WORKSHOP			
9:00 AM	10:45 AM	Raymond Byrne Patrick Balducci Howard Passell Will McNamara Bobby Jeffers Jeremy Twitchell Dhruv Bhatnagar	Facilitator, Sandia National Laboratories Facilitator, Pacific Northwest National Laboratory Sandia National Laboratories Sandia National Laboratories Sandia National Laboratories Pacific Northwest National Laboratory Pacific Northwest National Laboratory
10:45 AM	11:00 AM	**BREAK**	
11:00 AM		**PEER REVIEWER EVALUATIONS DUE** BAG LUNCH	
SESSION WRAP-UP			
11:00 AM	12:00 PM	Vince Sprenkle / Wei Wang Michael Starke Babu Chalamala Dr. Imre Gyuk	Pacific Northwest National Laboratory Oak Ridge National Laboratory Sandia National Laboratories DOE Office of Electricity

POSTER SESSIONS

TUESDAY, 24 SEPTEMBER 2019

RELIABILITY	
Multi-scale Thermal Stability Study of Lithium-ion Batteries as a Function of Chemistry and State of Charge	Yuliya Preger, Sandia National Laboratories
Durability and Reliability of Commercial Lithium-ion Cells as Function of Chemistry and Cycling Conditions	Yuliya Preger, Sandia National Laboratories
Heat Release from Thermal Decomposition of Layered Metal Oxide Cathodes in Lithium-ion Batteries	Randy Shurtz, Sandia National Laboratories
Energy Storage Models for Risk Optimization	David Rosewater, Sandia National Laboratories
Recommended Practice for Battery Management Systems in Stationary Energy Storage Applications	David Rosewater, Sandia National Laboratories
Reliability Testing of Li-ion Batteries for Stationary Applications	Daiwon Choi, Pacific Northwest National Laboratory
Reliability Test Laboratory Update	David Reed, Pacific Northwest National Laboratory
In-situ Reliability Studies of Vanadium Redox Flow Batteries: High Voltage Stressors	Rajankumar Patel, Pacific Northwest National Laboratory
ANALYTICS	
A Model Predictive Frequency Control of Low Inertia Microgrids with Energy Storage Systems	Reinaldo Tonkoski, South Dakota State University
Distributed Controls Using Energy Storage for Improved Grid Stability and Resilience	Roghieh Biroon, Clemson University
Energy Storage Planning for Clean Energy Target	Tu Nguyen, Sandia National Laboratories
Utilizing Existing Generation Fleet Using Large-Scale Energy Storage Systems	Tu Nguyen, Sandia National Laboratories
Opportunities for energy storage plus solar in CAISO	Raymond Byrne, Sandia National Laboratories
Siting Energy Storage for Resilient Distribution Systems	Randy Brost, Sandia National Laboratories
Continuous-time Look-Ahead Scheduling of Energy Storage in Real-time Markets	Bosong Li, Masood Parvania (PI)

MATERIALS II	
Advanced Membranes for Flow Batteries: Anion Exchange Membranes	Cy Fujimoto, Sandia National Laboratories
Electrochemical Energy Storage through Ligand-Based Charge Manipulation	Mitchell Anstey, Davidson College
Next Generation Cell design and Material Optimization for Sodium Batteries	Stephen Percival Sandia National Laboratories
Solid State Separator Development for Sodium-Based Batteries	Amanda Peretti, Sandia National Laboratories
Radialene Radicals for Aqueous Redox Flow Batteries	Christopher Bejger, The University of North Carolina at Charlotte
Materials and Membranes for High Energy Density Non-Aqueous Redox Flow Batteries	Ethan Self, Oak Ridge National Laboratory
Elucidating Molecular Transport through Membranes in Flow Batteries	Leo Small, Sandia National Laboratories
Materials and Membranes for High Energy Density Non-Aqueous Redox Flow Batteries	Jagjit Nanda, Oak Ridge National Laboratory
Lithium-Pretreated Hard Carbon as High-Performance Sodium-ion Battery Anodes	Biwei Xiao, Pacific Northwest National Laboratory
Development of Sulfide based solid state Electrolytes for Na-ion Batteries	Donghai Wang, Pacific Northwest National Laboratory
Monitoring the State-of-Charge of a Vanadium Redox Flow Battery with the Acoustic Attenuation Coefficient: An In Operando Noninvasive Method	Xiaoqin Zang, Pacific Northwest National Laboratory
Regenerated hydrogen-iron flow cell for low-cost distributed long-duration energy storage	Litao Yan, Pacific Norhtwest National Laboratory
POWER ELECTRONICS	
Extreme Solar: Towards 24-7 Renewable Energy	Valerio De Angelis, Urban Electric Power Satish Ranade, New Mexico State University
Connecting Alaska Remote Villages using Medium Voltage Intertie System	Mariko Shirazi, University of Alaska Fairbanks
GLIDES: Delivering Efficient, Flexible Energy Storage	Ayyoub Momen, Oak Ridge National Laboratory

POWER ELECTRONICS (CONTINUED)	
Advanced Power Electronics for Grid Storage	Satish Ranade, New Mexico State University
Advanced Capacitors for Future Power Conversion System	Bruce Gnade, Southern Methodist University
X7R Ceramic Capacitor Lifetime for Pseudo-DC-link Topologies	Jon Bock, Sandia National Laboratories
Advanced Gate Dialectrics for Wide-Bandgap Devices	Peter Dickens, Sandia National Laboratories
Wide Bandgap Power Electronics Reliability	Bob Kaplar, Sandia National Laboratories
Advanced Power Conversion Systems featuring SiC MOSFETs with In-Situ Restoration Capabilities	Ranbir Singh, GeneSiC Semiconductor
Advanced Power Electronic System for Integration of Multibattery Secondary Use Energy Storage Systems	Madhu Chinthavali, Oak Ridge National Laboratory
Residential Deployment of a Secondary Use Energy Storage System	Michael Starke, Oak Ridge National Laboratory
Engineering Routes Towards Synthesis and Performance of Layered Oxide Cathode Materials for Sodium-ion Batteries	David Wood III, Oak Ridge National Laboratory
Design and Fabrication of High-Temperature Optocoupler For High-Density Power Module	Zhong Chen, University of Arkansas
Medium-voltage Power Electronics for Grid-tied Energy Storage	Kristen Booth, The Ohio State University
Smart GaN-based Inverters for Grid-tied Energy Storage Systems	Medhi Ferdowsi, Innocit
Predicting Reliability, Improving Safety and Resiliency in Grid Connected Battery Energy Storage Systems	Harish Sarma Krishnamoorthy, University of Houston

EQUITABLE REGULATORY ENVIRONMENT	
Planning Considerations for Energy Storage in Resilience Applications	Jeremy Twitchell, Pacific Northwest National Laboratory
INDUSTRY ACCEPTANCE	
Technical Challenges for Energy Storage in Metro Rail Applications	Kevin Blackman, Helix Power Corporation Matthew Lazarewicz, Helix Power Corporation
The BEAM Training Center at Santa Fe Community College	Stephen Gomez, Santa Fe Community College
The Nanogrid at Santa Fe Community College	Stephen Gomez, Santa Fe Community College
BESS Control of A Grid to Liberate Renewables	Clay Koplin, Cordova Electric Cooperative (CEC)
Global Energy Storage Database (GESDB) Updates	Sam Roberts, Sandia National Laboratories
CESA State Energy Storage Policy Initiatives	Todd Olinksy-Paul, Clean Energy States Alliance (CESA)
Eugene Water and Electric Board / Korean Consortium Energy Storage Project	Kendall Mongird, Pacific Northwest National Laboratory
Microgrid Evaluation Tool	Di Wu, Pacific Northwest National Laboratory
Washington Clean Energy Fund Economics	Patrick Balducci, Pacific Northwest National Laboratory
Modeling the Nantucket Energy Storage System	Vanshika Fotedar, Pacific Northwest National Laboratory Xu Ma, Pacific Northwest National Laboratory
Battery State of Health Model	Vish Viswanathan, Pacific Northwest National Laboratory Alasdair Crawford, Pacific Northwest National Laboratory
Energy Storage Control Capability Expansion at Portland General Electric's Salem Smart Power Center	Jan Alam, Pacific Northwest National Laboratory
Energy Storage Planning Efforts for Regional Demonstrations Projects	Alexander Headley, Sandia National Laboratories
Safety considerations for BESS: Before, During and After Commissioning	Susan Schoenung, Longitude 122 West

INDUSTRY ACCEPTANCE (CONTINUED)	
State Regulatory Commission Energy Storage Outreach and Education	Howard Passell, Sandia National Laboratories
Sandia National Laboratories Demonstration Summary	Ben Schenkman, Sandia National Laboratories Dan Borneo, Sandia National Laboratories
MATERIALS I	
Effect of ZnO-Saturated Electrolyte on Rechargeable Alkaline Zinc Batteries at High Depth-of-Discharge	Matthew Lim, Sandia National Laboratories
Zincate-Blocking Polymeric Separators for Zn/MnO2 Batteries	Igor Kolesnichenko, Sandia National Laboratories
Rechargeable Zinc Manganese Dioxide Batteries: From Concept to Product	Jinchao Huang, Urban Electric Power
Real-Time Identification and Understanding of Zinc Compounds in Rechargeable Zinc Electrodes	Brendan Hawkins, City College of New York
Theoretical Studies of the Electrochemical Properties of Bi- and Cu-Modified d-MnO2 Electrodes in Rechargeable Zn/MnO2 Batteries	Birendra Ale Magar, New Mexico State University
Effects of Water-Soluble Binders on Electrochemical Performance of Manganese Dioxide Cathode in Mild Aqueous Zinc Batteries	Hee Jung Chang, Pacific Northwest National Laboratory
Development of Zinc-Based Anodes for Aqueous MnO2/Zn based Batteries	Matthew Fayette, Pacific Northwest National Laboratory
Enabling Natural Graphite in High Voltage Aqueous Zinc-Graphite Dual Ion Batteries	Ismael Rodriguez Perez, Pacific Northwest National Laboratory
Electrochemically Produced Zinc Oxide Electrode in Rechargeable Alkaline Batteries	Snehal Kolhekar, City College of New York
Rechargeable Solid-State Copper Sulfide Cathodes for Alkaline Batteries: Importance of the Copper Valence State	Jonathon Duay, Sandia National Laboratories

SAFETY PERFORMNCE	
Abuse Test Development: Mechanisms and Materials Impact of Abused Lithium-ion Batteries	Loraine Torres-Castro, Sandia National Laboratories
Mitigation of Failure Propagation in Multi-Cell Lithium Ion Batteries	Loraine Torres-Castro, Sandia National Laboratories
Predicting and Mitigating Cascading Failure in Stacks of Lithium-Ion Cells	Andrew Kurzawski, Sandia National Laboratories
Thermal Runaway Testing and Database Development of Large-format Li-ion Cells at ORNL and SNL	June Stanley, Sandia National Laboratories
Internal Pressure Measurements during the Thermal Runaway of Cylindrical Lithium ion Batteries	Frank Austin Mier, New Mexico Tech
PARTNERSHIPS: ACADEMIA, INDUSTRY, PROFESSIONAL ORGANIZATIONS, STANDARDS BOARDS	
Energy Resilience for the Seminole Tribe	Frank Currie, Sandia National Laboratories
Rural Electricity Resilience on the Navajo Nation	Frank Currie, Sandia National Laboratories
Energy Storage in the Future Puerto Rico Electric Grid	Frank Currie, Sandia National Laboratories
Update on the Natural Energy Laboratory of Hawaii Authority ESS and Microgrid Projects	Laurence Sombardier, Natural Energy Laboratory of Hawaii Authority (NELHA)
Energy Storage Valuation at San Carlos Apache Tribe	Rodrigo Trevizan, Sandia National Laboratories

NOTES

ABSTRACTS

POSTDOC PRESENTERS

Operando Investigations of Bismuth Additives on the Rechargeability of MnO_2 in Alkaline Batteries

Adrea Bruck, Northeastern University
Matthew Kim, Northeastern University
Josh Gallaway, Northeastern University (PI)

Zn/MnO_2 alkaline batteries have been identified as a viable option for the modernization of grid scale energy storage due to their projected cost (~\$50/kWh), scalability, and safer components when compared to non-aqueous alternatives. For this system to reach its maximum capacity, the full $Mn^{4+/2+}$ redox couple must be reversible over thousands of cycles with high mass loading. This was successfully demonstrated with the incorporation of various electrode constituents which alter the fundamental discharge and charge process of MnO_2 to $Mn(OH)_2$. By incorporating Bi_2O_3 into the composite electrode we show the complete reversibility of the layered, birnessite-type phase. Using non-destructive, synchrotron diffraction techniques, new insights into the phase changes occurring during active electrochemical cycling was extensively investigated with a new mechanism proposed. Further spectroscopic evidence including Raman and X-ray absorption spectroscopy during cycling also provides crucial insights into amorphous phases and variations in redox activity, with and without the Bi_2O_3 additive. Understanding the effects of bismuth containing constituents on the redox transitions of MnO_2 is critical to the development of rechargeable alkaline batteries by advancing the fundamental design of these systems.

Interfacial Engineering in Sodium Batteries

Martha Gross, Sandia National Laboratories
Erik Spoerke, Sandia National Laboratories (PI)

High temperature operation of traditional molten sodium batteries has limited their widespread deployment for grid-scale applications. Low temperature molten sodium batteries, however, show promise as safe, cost-effective, reliable energy storage systems. Reducing operating temperatures from ~300°C to near 100°C, however, introduces new challenges to interfacial wetting and charge transfer efficiency, not common in higher temperature batteries. The focus of this work has been to explore materials solutions to challenges at interfaces between the solid separator, the molten sodium anode, the molten salt catholyte, and the current collector. With emphasis on improved interfacial wetting, redox kinetics, and charge transfer efficiencies, improvements in material performance has led to exciting improvements in overall battery performance at low operating temperatures.

Energy Storage Planning Efforts for Regional Demonstrations Projects

Alexander Headley, Sandia National Laboratories
Tu Nguyen, Sandia National Laboratories (PI)

Sandia National Labs engages with a number of external entities to assess the value of energy storage systems in their situation and help them select appropriate parameters for proposal requests. Here, two such valuation studies with unique considerations are presented: community distributed solar generation in New York and the NELHA research campus in Hawaii. In NY, recent changes intended to incentivize proper timing and placement of distributed generation have increased the potential for energy storage in the area. The NELHA research campus could benefit from energy storage given a significant influx of photovoltaic generation, but upcoming operation of a large, potentially flexible hydrogen production facility would significantly affect the value proposition of energy storage in this case. General lessons learned from these and other valuation analyses will be presented.

Zincate-Blocking Polymeric Separators for Zn/MnO_2 Batteries"

Igor Kolesnichenko, Sandia National Laboratories

Recent advances have demonstrated that rechargeable Zn/MnO_2 batteries have significant potential for electrical grid storage applications due to their low cost, high energy density, and established materials supply chain. However, one of the main battery failure mechanisms currently limiting overall battery lifetimes is the dissolution and crossover of zinc [as zincate, $Zn(OH)_4^{2-}$] from the anode to the MnO_2 cathode, where it can react with soluble Mn(III) species to form irreversible phases such as $ZnMn_2O_4$ and/or deposit as insulating ZnO. In this work we demonstrate the applicability of several permselective polymeric separators for use in higher depth of discharge Zn/MnO_2 batteries at faster rates. Screening of the separators for zincate versus hydroxide crossover showed a strong selectivity for hydroxide, while ionic conductivity measurements showed comparable values to those of commercial CelgardTM 3501 and Cellophane 350P00 separators. Finally, preliminary data from cycling the full 2e– capacity of MnO_2 in the presence of our separators compared to the aforementioned commercial standards has shown promising improvements toward the eventual goal of use in real-world applications.

Effect of ZnO-Saturated Electrolyte on Rechargeable Alkaline Zinc Batteries at High Depth-of-Discharge
Matthew Lim, Sandia National Laboratories

Zinc anodes in rechargeable alkaline Zn/MnO_2 and Zn/Ni batteries are known to suffer from redistribution of active material due to the high solubility of ZnO in the electrolyte, leading to capacity loss and limiting their lifetime. In this work, we investigate pre-saturating KOH electrolyte with ZnO as a strategy to mitigate this issue in Zn/Ni cells. In contrast to previous reports of this approach, we use more commercially relevant limited-electrolyte cells and systematically study ZnO saturation at different levels of zinc depth-of-discharge (DOD), where the dissolved ZnO is included in the total system capacity. Under similar testing protocols at higher KOH concentrations, cells with ZnO-saturated electrolyte last significantly longer with similar energy efficiency to cells with ZnO-free electrolyte cycled at the same DOD. In addition, anodes cycled in the ZnO-saturated electrolyte develop more favorable compact zinc morphologies with less overall mass loss.

Reliability Testing of Lead Acid Battery Module for grid services
Nimat Shamim, Pacific Northwest National Laboratory
David Reed, Pacific Northwest National Laboratory (PI)

The advanced or carbon-enhanced negative electrode lead acid battery modules are a profitable option for renewable Energy Storage Applications due to its' high cycle life, low cost and sustainability, However, there is still a lot to understand in terms of reliability for grid services. In this work, a lead acid battery modules' round-trip efficiency (RTE), charge/discharge capacity, cumulative discharge energy is measured for grid duty cycle such as frequency regulation. Capacity test and pulse resistance test has also been done to measure the degradation based on capacity loss and resistance respectively. The results will be analyzed to characterize the performance reliability of lead acid battery module for grid services. In future, peak shaving testing will be performed. These results will be compared with other battery chemistries to determine a reliable application specific battery technology for grid services.

Synthesis of Advanced Magnetic Materials for Inductors and Transformers
Tyler Stevens, Sandia National Laboratories
Todd Monson, Sandia National Laboratories (PI)

The size requirements of power electronics are determined by the necessary components. Magnetic materials contribute to this significantly, and to maximize efficiency and size, new magnetic materials are required. One of the main challenges has been developing materials that work in conjunction with high frequency semiconductor switches. This year we have focused on identifying and optimizing synthetic routes to yield phase pure iron nitrides and then incorporating them into composites. This has resulted in materials with good performance up to 1 MHz.

Dihydroxyphenazines as Anolytes for Aqueous Redox Flow Batteries
Nadeesha Nambukara Wellala, Pacific Northwest National Laboratory
Aaron Hollas, Pacific Northwest National Laboratory (PI)

Aqueous Organic Redox flow batteries have gained increasing attention as a promising candidate in grid energy storage, because of their synthetic tunability, use of earth-abundant elements, and potentially low cost. Previously reported phenazine-based anolytes (e.g. 7,8-dihydroxyphenazine-2-sulfonic acid, DHPS), although high capacity, still face the challenges of, self-reduction and desulfonation side reactions along cycling. To improve performance and identify more promising functionalization patterns, dihydroxyphenazine isomers have been synthesized and the effect of substitution pattern on solubility and stability has been determined.

POSTDOC PRESENTERS

Advanced Cathodes for Intermediate-Temperature Na-Metal Halide Batteries

Xiaowen Zhan, Pacific Northwest National Laboratory
Guosheng Li, Pacific Northwest National Laboratory (PI)

Sodium (Na)-based battery technologies, which are economical (because Na is abundant) and have long cycle life, are gaining importance for large-scale energy storage applications. Among the widely studied Na-based battery systems, intermediate-temperature (IT) Na-metal halide (Na-MH) batteries have demonstrated several advantages over conventional high-temperature Na batteries, including superior battery safety, lower operating temperature and manufacturing cost, potentially longer cycle life, and easier assembly. However, the rate performance of IT Na-MH batteries is inevitably affected by the lower operating temperatures. Here, we present our recent study on NiBr2 (NaBr/Ni) and NiI2 (NaI/Ni) cathode materials beyond the extensively investigated NiCl2. The NaBr/Ni cathode shows the highest energy density of 174 Wh/kg at 33.3 mA/cm2 (~0.8C), which is 2.5 and 1.9 times higher than those of NaCl/Ni and NaI/Ni cells. The underlying enhancement mechanism and the synergetic effects of anion chemistry on the electrochemical properties will also be discussed.

NOTES

The Overview of the DOE OE Energy Storage Program
Dr. Imre Gyuk – Department of Energy OE Energy Storage Program

The Department of Energy's Office of Electricity (DOE OE) serves the national interest. The OE's electric utility grid priorities include reliability, resilience, cyber integrity, and full technology utilization. The Energy Storage Program pursues these goals using four pillars: system safety and reliability performance, industry acceptance, equitable regulatory environment engagement, and cost-effectiveness of materials, devices, and systems. The work of the DOE OE Energy Storage Program is conducted primarily through the collaborative efforts of three national laboratories (Sandia National Laboratories, Pacific Northwest National Laboratory, and Oak Ridge National Laboratory) and their partnerships with academia, industry, and professional organizations. The activities vary from research and development, bench and field testing and analyses, systems deployment and demonstrations, workshops, policy analysis and applications, technical conferences, and contributions to peer-reviewed journals and proceedings. The annual DOE OE peer review on energy storage is where all things culminate and are reported in an open forum that includes the progress of the research, the growth of projects, and the potential path for future work. Third party subject matter experts serve as observers and evaluators.

Partnerships

2020 Biennial Energy Storage Review
Ramteen Sioshansi, The Ohio State University

This talk provides an introduction to the Electricity Advisory Committee, its Energy Storage Subcommittee, and the 2020 biennial assessment and review of the Department of Energy's energy storage-related research, development, and deployment activities.

Engaging Academia: Creating Productive Networks
Erik Spoerke, Sandia National Laboratories

This presentation will highlight creative and productive networks and collaborations between national laboratories and academic institutions across the country. These are diverse relationships that inspire creative new ideas and allow Office of Electricity programs to benefit from expertise and innovation that are hallmarks of quality academic partners. Meanwhile, university partners benefit from opportunities to explore the application of their creative energy storage ideas and work with National Lab experts focused on multiscale energy storage development programs typically grander than the scope of an individual principal investigator. These collaborations continue to be highlights of the Office of Electricity Energy Storage program with potential to advance critical new energy storage technologies.

Update on Energy Storage System Reliability Codes & Standards Activities
Charlie Vartanian, Pacific Northwest National Laboratory

Codes & Standards (C&S) help assure prudent industry practices are implemented equitably and efficiently. With emergence of newer advanced technologies and applications for grid connected Energy Storage Systems (ESS), having supporting C&S is critical to maintaining an aggressive rate of industry adoption of ESS. This presentation gives an update on a project to facilitate creation and adoption of ESS Reliability C&S, including the first IEEE Std. 1547.9 Guide to Interconnection of DER Energy Storage. This project focuses on Reliability C&S. This relatively new PNNL OE ES activity complements and builds on the DOE OE ES supported work to facilitate ESS Safety C&S. However, the industry communities that oversee grid reliability standards (e.g. NERC) are generally disparate from Safety C&S communities.

Energy Storage Projects Team Overview
Daniel Borneo, Sandia National Laboratories

Energy storage is a key to enabling modernization of the electricity grid, including the successful integration of renewable and distributed energy technologies. The DOE OE Energy Storage Program uses its Demonstrations Team at Sandia National Laboratories to address multiple challenges to the widespread deployment of energy storage: cost, creation of an equitable regulatory environment, safety and reliability, and industry acceptance. The team supports development, deployment, and research across multiple storage technologies and applications from transmission constrained regions in Alaska to hurricane-prone Puerto Rico, and from the off-grid rural corners of the Navajo Nation to the leading edge of emerging educational programs.

Equitable Regulatory Environment

Overview of Equitable Regulatory Environment Programs at PNNL
Jeremy Twitchell, Pacific Northwest National Laboratory

The Equitable Regulatory Environment thrust area of the Energy Storage Program is charged with reducing institutional and regulatory hurdles to energy storage. This presentation will discuss PNNL's efforts in this area during FY 2019 and summarize key deliverables, including publications, presentations, and technical assistance to states.

Regulatory Insights from the Southeastern Energy Storage Workshop
Rebecca O'Neil, Pacific Northwest National Laboratory

In July 2018, the Energy Storage Program conducted a workshop on energy storage topics for state regulatory staff from the Southeastern and Mid-Atlantic regions. The event drew 25 regulators from nine states. This presentation will share lessons learned during a roundtable discussion at the workshops in which the state representatives shared the specific regulatory issues that energy storage has raised in their states. The discussion provides valuable insight into emerging state needs that may inform future Equitable Regulatory Environment efforts

An Energy Storage Valuation Handbook for Regulators
Dhruv Bhatnagar, Pacific Northwest National Laboratory

The DOE Energy Storage program has made considerable efforts at characterizing the value streams of energy storage in general and conducting project-specific economic evaluations. This effort is developing a handbook for regulators, other state agencies and lawmakers that summarizes the work done by the storage program on valuation and condenses the various valuation techniques and tools developed into a easily accessible handbook for policymakers and decisionmakers. This effort builds upon the a similar handbook developed by the storage program in 2012.

Valuation of Energy Storage in the US Electricity and Frequency Regulation Markets
Felipe Wilches-Bernal, Sandia National Laboratories

Around 60% of the US electric power supply is managed through competitive markets. The price of wholesale electricity and of ancillary services required to maintain the system operating reliably is obtained via market mechanisms. This presentation will discuss how energy storage systems can benefit from arbitrage and providing frequency regulation (one of the key ancillary services) in the seven different US electricity market areas. Revenue differences stemming from the different implementations of the frequency regulation market and pricing data will be presented. Additionally, the sensitivity of the revenue in every market area with respect to parameters of the energy storage system will be analyzed.

Energy Storage Policy Initiatives
Will McNamara, Sandia National Laboratories

This presentation will provide an overview of SNL's current initiatives to expand coverage and analysis of policy issues at both the federal and individual state levels that impact energy storage. Specific activities including updating of the SNL Energy Storage Database with information on legislative and regulatory policy at the states that are leading the effort to define policy for energy storage; outreach to public utility commissioners; improving visibility and interaction with industry associations such as NRECA, NERC, NARUC; and publication of analytical white papers on energy storage policy issues. The expansion of this area supports broader F20 goals for our group, including enhancing the external engagement of the department, strengthening the technical scope of the department, and improving the global visibility of the Sandia Grid Energy Storage Program.

Industry Acceptance

Nantucket Island Energy Storage System Assessment
Patrick Balducci, Pacific Northwest National Laboratory

Nantucket Island, which is located off the coast of Massachusetts, has a fairly small resident population of approximately 11,000 but during summer months, the population on the island can swell to over 50,000 creating times during the year where load could exceed the N-1 capacity of the island's electrical grid. Rather than investing in a high-cost 3rd submarine transmission cable to expand capacity to the island, National Grid has instead chosen to invest in a combustion turbine generator (CTG) with a temperature-dependent capacity that varies between 10 MW and 16 MW and a 6 MW / 48 MWh Tesla lithium-ion battery energy storage system (BESS). In consultation with National Grid, Pacific Northwest National Laboratory (PNNL) defined a set of services to be evaluated from an economic perspective based on its experience in conducting similar assessments for various utilities across the U.S. While the primary service provided by the BESS is N-1 contingency events that will defer investment in a third submarine transmission cable, there are additional local and market-based benefits that the BESS can also provide, including outage mitigation, volt-VAR operations/conservation voltage reduction, capacity, frequency regulation, spinning reserves, and energy arbitrage. This presentation presents the results of this assessment, including the return on investment associated with the CTG and BESS investment, and control strategies designed to realize these benefits in real-time.

Demonstration of Energy Storage Benefits Around the Nation
Ben Schenkman, Sandia National Laboratories

Demonstration projects of how energy storage can benefit various entities is the main focus of the Energy Storage Demonstration Team. Project partners Sandia is collaborating with are Cordova Electric Cooperative, National Rural Electric Cooperative Association, Helix, Alliant Energy, Santa Fe Community College, Eugene Water and Electric Board, Navajo Tribal Utility Authority, Seminole Tribe of Florida, Electric Power Board, Arizona Public Services, Natural Energy Laboratory of Hawaii Authority, Alaska Center for Energy and Power, Iowa State University, Albuquerque Public Schools, UniEnergy Technologies, Urban Electric Power, New Mexico State University, and California Energy Commission. Analytics are performed during each project to determine the optimal size of energy storage needed to maximize revenue or resiliency which then can be used to develop a request for proposals. Sandia then works with its partners to commission the energy storage system and collect performance data from the energy storage systems. This data is used to create high fidelity models of the energy storage systems as well as understanding degradation and how to optimize the energy management and battery management systems.

Microgrid Evaluation Tool
Di Wu, Pacific Northwest National Laboratory

Approaches for designing and operating a microgrid with various distributed energy resources (DERs) including renewable generation and energy storage have received increasing attention during the past few years. In this work, we develop a methodology and tool to determine optimal sizes of various DERs considering both economic benefits and resilience performance of a microgrid. We model the interdependency between DER capacity and operation, and thereby simultaneously determine their optimal sizes and dispatch. To better capture the operation of DERs and their impacts on economic benefits and system resilience under diversified conditions, we model hourly microgrid operation over representative years and consider a population of stochastic grid disturbances. With the piecewise linearization technique, the optimal sizing problem is formulated using mixed-integer linear programming that can be efficiently be solved even with a large number of system operating conditions.

Helix Power: Technical Challenges for Energy Storage in Metro Rail Applications
Kevin Blackman, Helix Power Corporation

Metro systems present significant challenges in power delivery. 30-50%of energy regenerated by metro braking energy is wasted as heat but can be recycled to reduce train acceleration. Successful recycling will require energy storage that can meet all of the tech requirements simultaneously::

- Charge/discharge 1,000,000 full depth-of-discharge cycles in a 20-year lifetime
- Operate 4hrs continuously at a 1MW – 90 second C-40 rate

- Small form factor that physically fits into a subway system
- Provide 3rd party validation for commercialization

BESS Control of A Grid to Liberate Renewables

Clay Koplin, Cordova Electric Cooperative (CEC)

A SAFT/ABB BESS system has been integrated into the community-scale microgrid of CEC in the remote community of Cordova, Alaska. The BESS will be automated to operate parallel to a diesel generation power plant and two run-of-river hydroelectric plants. By operating in isochronous (grid-forming or "island") mode, the BESS provides this grid service instead of the hydroelectric projects at a savings of up to 750kW of renewables, or the diesel at a savings of starts/stops and reduced number of dispatched units. The BESS will also charge and discharge for local grid for hydro-diesel arbitrage, and will potentially serve as emergency power supply to critical loads.

Materials I

Zn/MnO2 Batteries

Timothy Lambert, Sandia National Laboratories

Rechargeable zinc/manganese oxide (Zn/MnO2) batteries are a leading energy storage technology that is based on safe, abundant and low cost materials with an existing supply chain and large scale manufacturing opportunities. Energy densities of ~ 400 Wh/L at costs of < \$50/kWh, when produced at scale, should be achievable once certain technical barriers have been removed. For example, the ability to reliably increase the cycled capacity of Zn while also preventing the deleterious effects of Zn crossover from the anode to the MnO2 cathode are two key obstacles that must be overcome in alkaline Zn/MnO2 batteries. This presentation will highlight annual advances in furthering the development of Zn/MnO2 battery chemistry and technology within the Office of Electricity energy storage portfolio.

Progress on the development of the Zn-MnO2 rechargeable battery

Sanjoy Banerjee, City College of New York

Zinc (Zn) and manganese dioxide (MnO2) have been demonstrated as promising electrochemical energy storage materials due to the high energy density, low cost, and outstanding safety characteristics. A rechargeable Zn/MnO2 system would bring a revolutionary low-cost solution for grid-scale energy storage. However, the poor reversibility of the traditional Zn and MnO2 materials has limited the achievable energy density and cycle life. Recent developments in rechargeable Zn/MnO2 batteries achieved by the City University of New York Energy Institute (CUNY-EI) in partnership with Urban Electric Power, Inc. (UEP) has presented unique characteristics that could potentially disrupt existing technologies. In this talk, the challenges and progress in developing and commercializing rechargeable Zn/MnO2 batteries for energy storage will be presented.

High Voltage Zn-MnO2 batteries: Making Zn the new Li

Gautam Yadav, Urban Electric Power

Significant breakthroughs have recently been made in developing a rechargeable high voltage zinc-manganese dioxide battery. As presented by Gautam Yadav, initial lab results achieved at The City College of New York have demonstrated ZnMnO2 battery cells exceeding the 2V barrier commonly accepted in aqueous zinc chemistry. With a voltage of 2.45-2.8V, the alkaline ZnMnO2 battery developed by Dr. Gautam G. Yadav and his group in the CUNY Energy Institute, could challenge lithium (Li)-ion batteries in a variety of markets, including electric vehicles. This technology has the promise for truly groundbreaking advancements in energy storage.

Discharge Mechanism of MnO2 in Deep-Cycle Rechargeable Zn/MnO2 Batteries

Igor Vasiliev, New Mexico State University

Electrical energy storage is essential for seamless integration of intermittent renewable energy sources into the power grid. Rechargeable batteries made from low-cost and environmentally benign materials are attractive for large-scale energy storage. We apply first-principles density functional computational methods to study the discharge mechanism of MnO2 in rechargeable alkaline Zn/MnO2 batteries. The results of our calculations are used to predict the most probable redox reaction pathways in the MnO2 electrode. Based on our theoretical model, we analyze the electrochemical processes leading to the formation of irreversible discharge reaction products in the MnO2 electrode and discuss the influence of Bi and Cu additives on the cycle life of rechargeable alkaline Zn/MnO2 batteries.

Advanced Manganese Oxide-based Cathodes for Rechargeable Aqueous Zinc-ion Batteries
Xingbo Liu, Pacific Northwest National Laboratory

The aqueous rechargeable Zn-ion batteries (ZIBs) have emerged as a promising electrochemical energy storage system especially for grid-level application, due to their low cost, high safety, low flammability and simple manufacturing process. The common MnO_2 cathodes of ZIBs in mildly acidic or near neutral electrolytes always suffer from low surface areas, serious structural degradation and Mn dissolution, leading to poor cycling stability and rate performance and demonstrate elusive electrochemical mechanisms. Therefore, the overall goal of this program is to develop high-performance manganese oxide-based cathodes through engineering crystal structures and surface properties. In this year, we have developed nanostructured MnS as a pre-electrode which will be in situ converted to active layered manganese oxide cathode with large electrochemically active surface areas during the cycling activation of ZIBs and revealed the mechanistic understanding of the electrochemical process. The surface roughening, re-crystallization and micro-structural reconstruction during the charge-discharge process enable the exposure of abundant active sites and defects for the formed manganese oxide, rendering large specific capacity, favorable ion transfer kinetics, high rate performance and cycling stability for 4000 cycles at 3 A g^{-1}, superior to those of a-MnO_2 nanowires benchmark cathode.

Rechargeable Solid-State Copper Sulfide Cathodes for Alkaline Batteries: Importance of the Copper Valence State
Jonathon Duay, Sandia National Laboratories

Batteries for grid storage applications must be inexpensive, safe, reliable, as well as have a high energy density. Here, we utilize the high capacity of sulfur (S) (1675 mAh g^{-1}, based on the idealized redox couple of S^{2-}/S) in order to demonstrate for the first time, a reversible high capacity solid-state S-based cathode for alkaline batteries. It was found that in order for the S cathode to have the best cycle life in the solid-state it must not only be bound to Cu ions but bound to Cu ions in the +1 valence state, forming Cu_2S as a discharge product. Zn/Cu_2S batteries based on this chemistry provided a grid storage relevant energy density of > 42 W h L^{-1} (at 65 wt. % Cu_2S loading), despite only using a 3% depth of discharge (DOD) for the Zn anode. This work opens the way to a new class of energy dense grid storage batteries based on high capacity solid-state S-based cathodes.

Safety Performance

Thermal Runaway Risks for Li-ion Batteries in Energy Storage Systems
Hsin Wang, Oak Ridge National Laboratory

Li-ion batteries of different capacities and state-of-charge have been subjected to indentation testing developed at ORNL and Sandia. Using the test protocol, cell voltage, temperatures, indentation load and displacement are recorded during and after the tests. These results along with cell specifications are used as inputs for machine learning package to find out the most sensitive parameters related to thermal runaway risk. A database is being generated on Li-ion cell risk factors. The goal of the database development is to allow the cell users or manufacturers determine the thermal runaway risk by performing a simple, single SOC indentation test.

Abuse Test Development: Mechanisms and Materials Impact of Abused Lithium-Ion Batteries
Loraine Torres-Castro, Sandia National Laboratories

This work examines the application of Electrochemical Impedance Spectroscopy (EIS) and Differential Capacity calculations (dQ/dV) as tools for determining the state of stability (SOS) of an electrochemical cell or battery. The cells used for this study were commercial 10 Ah NMC pouch cells and 10Ah LFP cells subjected to electrical and thermal abuse coupled with EIS monitoring. This aims to not only provide a deeper understanding of how abused cells and batteries fail but also form the technical basis of a tool that could ultimately be used to interrogate cells of unknown stability and even monitor active cells for early signs of damage or failure. Fast impedance monitoring hardware previously developed at Idaho National Laboratory is used to provide not only monitoring after an abusive battery test but also look for changes in the cell while abusive conditions are applied. Differential capacity calculations are explored both before tests and after moderate levels of abuse to explore any noticeable changes that may be monitored during charge and discharge operations. The electrochemical techniques are supported with materials evaluations to further understand the impact of abusive conditions on the constituent materials.

Predicting and Mitigating Cascading Failure in Stacks of Lithium-Ion Cells
John Hewson, Sandia National Laboratories

Whether or not a single point failure leads to a larger cascading failure depends on the system's ability to dissipate inadvertently released energy. We discuss predictive modeling of both inadvertent energy release and the dissipation of that energy. Predictive modeling also points out the limits of propagation offering the opportunity for sufficiently well validated models to define system designs that mitigate risks of localized failures. We use a series of Sandia cell-stack propagation measurements to assess the ability of predictive models to put bounds on predictive system analysis at the cell-stack level.

Update on Energy Storage System Safety Codes & Standards Activities
Matthew Paiss, Pacific Northwest National Laboratory

This presentation provides an update on the creation and adoption of Energy Storage System (ESS) Safety Codes & Standards (C&S). With the recent development of NFPA's first standard (855) covering the design, installation, operation and decommissioning of ESS, this topic has received significant attention across various stakeholders including users, enforcers, and designers of ESS. PNNL's focus on both Reliability and Safety CS, provides for a broad view and involvement in the C&S development process. Additionally, a brief overview of resulting Fire Code amendments resulting from a recent ESS failure will be discussed.

Reliability

Long-term Performance Assessment of Li-ion Battery Chemistries under Grid Services
Daiwon Choi, Pacific Northwest National Laboratory

Li-ion batteries are expected to play a vital role in stabilizing the electrical grid as solar and wind generation capacity becomes increasingly integrated into the electric infrastructure. In this work, commercial Li-ion batteries with different cathode chemistries including $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$ (NCA), $LiNi_xMn_yCo_zO_2$ (NMC) and $LiFePO_4$ (LFP) have been tested under the protocols recently developed for grid duty cycle such as frequency regulation (FR) and peak shaving (PS). The long-term performance comparison derived from capacity, round trip efficiency (RTE), resistance, charge/discharge energy, total utilized energy and degradation mechanisms of the different commercial battery chemistries will be presented and discussed. These results will be used as a guideline for future reliability testing, selection, deployment, operation and cost analyses of Li-ion batteries used for different applications.

Safety and Performance of Commercial Lithium-Ion Cells
Yuliya Preger, Sandia National Laboratories

Uncertainty about Li-ion based energy storage with respect to safety and reliability is a barrier for deployment. For the last several years Sandia has worked on a systematic comparison of various popular commercial Li-ion chemistries, including studies of: unintended abuse conditions within manufacturer specified operating conditions, thermal stability of whole cells and components, and long-term cycling performance. Recent research has taken a critical look at the materials aspects of thermal runaway and correlated contributions from individual cell components to thermal runaway trends. This systematic evaluation of component to whole cell degradation provides a scientific basis for future thermal modeling and design of safer cells. The performance of the same cells was also evaluated in long-term cycling, with variation of the discharge rate, depth of discharge (DoD), and environment temperature. Though all cells were cycled within manufacturer specifications, the time to reach 80% capacity varied by thousands of hours and cycle counts among cells of different chemistries and cycling conditions. The degradation of cells in this study was compared to that of similar commercial cells in previous studies to identify universal trends and to provide a standard deviation for performance. This comprehensive evaluation of commercial cells across abusive and non-abusive environments is intended to inform failure mitigation techniques. Detailed results of the individual studies are provided in the associated posters.

Heat Release from Thermal Decomposition of Layered Metal Oxide Cathodes in Lithium-Ion Batteries
Randy Shurtz, Sandia National Laboratories

Existing models of thermal runaway in lithium-ion batteries rely heavily on calorimetry measurements of battery components. While these methods are essential to calibrate model parameters that define chemical reaction rates, there are disadvantages to fully-empirical approaches when they are also used to define heats of reaction. This study examines various proposed decomposition schemes relevant to layered metal oxide cathodes and identifies the most plausible reaction pathways through comparison to the available species measurements and by comparing the thermodynamic heat release for the individual reaction steps to calorimetry measurements. Several modeling advantages emerge from this approach. First, reliance on both species data and consistency with thermodynamic heat release provides more information to identify the specific chemical transformations occurring. Eventually, this may include the ability to identify and explain variation in the extent of electrolyte oxidation based on experimental conditions. Second, uncertainties associated with total heat release measurements can be reduced through identification of an appropriate thermodynamic heat release. Likewise, heat release uncertainty can be deconvoluted from uncertainty associated with chemical reaction rates. Third, keeping thermal runaway models up-to-date becomes easier if fewer parameters need to be re-optimized when new materials are implemented in lithium-ion batteries. As the thermodynamic parameters governing heat release become well-understood, trends in the kinetic parameters can be identified and correlated so that safety predictions can be made for new material formulations a priori. These methods lead to thermal runaway models with better physics and improved predictive capabilities.

Battery State of Health Model
Vish Viswanathan, Pacific Northwest National Laboratory

A coupled electrochemical/thermal model has been developed for multiple Li-ion battery chemistries. Thermal effects include reversible heat loss/gain from entropy change and irreversible losses associated with polarization losses. The model estimates performance and performance degradation for various operating conditions. Degradation from the loss of lithium and loss of active material have been estimated by considering parallel paths for solid electrolyte interphase formation. This model, along with a top-down model has been validated against data presented in the literature.

Washington Clean Energy Fund Battery Testing Program Results
Alasdair Crawford, Pacific Northwest National Laboratory

The Washington Clean Energy Fund provided state funding for the purchase and deployment of four grid-scale BESSs, two vanadium flow batteries and two lithium ion battery systems. At each site, BESS technical performance was characterized using representative duty cycle profiles and reference performance tests. Results for metrics such as availability, round trip efficiency, energy capacity, internal resistance, and response time are provided. Additional analysis including power conversion system losses, auxiliary losses, and rate of change of temperature were compared across BESSs. A model has been developed to characterize the battery performance as a function of power and state of charge.

Analytics

Overview of Sandia's Energy Storage Analytics Work/ Equitable Regulatory Environment Thrust Area
Raymond Byrne, Sandia National Laboratories

The Equitable Regulatory Environment Thrust area of the Sandia energy storage program works to identify barriers to widespread energy storage deployment and develops technologies and tools to lower barriers. Energy storage valuation is often a complex task so a significant effort is placed on identifying methods for energy storage valuation for different applications and developing open-source tools that can be leveraged by industry. These algorithms and tools are often developed while assisting the DOE's energy storage demonstration projects via both technical and financial project evaluations. Other research areas include assessing the impact of policies on energy storage deployment, educating regulators, and identifying new value streams for energy storage (and the associated control algorithms).

Continuous-time Look-Ahead Scheduling of Energy Storage in Real-time Markets
Bosong Li, Masood Parvania (PI)

This poster presents a continuous-time look-ahead optimization model to schedule balancing and regulation services for energy storage (ES) systems in real-time markets. The proposed model co-optimized the services provided by the ES systems and generating units to minimize the total real-time system operation cost using the receding horizon control approach. Over each control horizon, the real-time load trajectory is forecasted and updated using a continuous-time Gaussian process. The continuous-time problem is projected to a finite-dimensional function space spanned by Bernstein polynomials and converted into a solvable mixed integer linear programming problem.

Operating Cost Model for Battery Energy Storage System
Tu Nguyen, Sandia National Laboratories

Currently, battery energy storage systems (BESS) is often assumed operating at no costs in power system analysis. In practice, there are costs associated with each kWh charged or discharged from a BESS due to energy losses and capacity degradation of BESS. In this work, we develop an operating cost model that take into account the efficiency and the degradation characteristics of electrochemical and redox flow BESSs. The model can be used in estimating the overall benefits of an BESS in providing grid services as well as in optimal dispatching multiple BESSs in a power system.

Energy Storage Financing & System Pricing Survey Study Series
Richard Baxter, Mustang Prairie Energy

The Energy Storage Financing study series is an outreach effort to the financial industry to help reduce and mitigate the risk of investing in energy storage technologies and projects. The goal is to reduce barriers of entry, reduce transaction costs, and promote wider access to low cost capital in order to accelerate energy storage project development. Studies to date have evaluated the roadmap for accelerating market growth, performance impacts on project financing, advancing contracting in energy storage, and project and portfolio valuation. The Energy Storage Pricing Survey series provides the energy storage industry with a standardized pricing benchmark for energy storage systems of a range of system sizes so customers can discover comparable prices at different system scales. The pricing survey is also intended to provide emerging energy storage technologies a widely accepted pricing benchmark.

Optimization Performance Evaluation Tool
Jan Alam, Pacific Northwest National Laboratory

The idea of optimal control of energy storage systems (ESSs) for individual or bundled use cases toward maximizing economic benefit is gaining popularity in the industry. Economic benefit generation with an ESS is typically an open-loop process. Considerable effort is given on developing and implementing optimal control strategies, however, little effort is given on analyzing how the economic value generated compares with the value anticipated. This presentation reports a task undertaken by PNNL to explore a concept to evaluate the economic performance of commercially available ESS control systems and potential avenues for improvement.

QuESt: An Energy Storage Application Suite
Ricky Concepcion, Sandia National Laboratories

QuESt is an open-source software application suite for energy storage valuation developed by the Sandia National Laboratories energy storage analytics group. The goal of this effort is to release useful and accessible tools based on Sandia's research to the public to assist in energy storage valuation in various use cases. This year the development team released several updates to QuESt, featuring the addition of QuESt BTM ("behind-the-meter"), an application in which users can estimate the cost savings provided by energy storage for time-of-use or net energy metering customers. This analysis draws from online databases/tools of U.S. utility rate structures, simulated building load profiles, and photovoltaic power profiles and exemplifies how energy storage can reduce time-of-use energy and demand charges.

Materials II

Elucidating Molecular Transport through Membranes in Flow Batteries
Travis Anderson, Sandia National Laboratories

Redox flow batteries are a promising technology for grid scale energy storage. This year we successfully elucidated mechanisms of transport in membranes for low cost aqueous-organic flow batteries and leveraged an OE-sponsored workshop to translate this knowledge to nonaqueous systems that offer higher voltages for more energy dense systems. We have sponsored several university collaborators who have developed new models and promising tunable materials for flow batteries. In all, we have developed a clearer understanding of the foundation of flow batteries: the interplay between solvent, salt, and membrane.

Materials and Membranes for High Energy Density Non-Aqueous Redox Flow Batteries
Jagjit Nanda, Oak Ridge National Laboratory

Redox flow batteries (RFBs) are promising energy storage devices for grid-level applications due to their long cycle life and the ability to independently scale their energy and power densities. To enable widespread adoption of nonaqueous RFBs, high energy density anolyte/catholyte systems and low-cost polymeric membranes which prevent crossover of redox-active species are required. This presentation will describe our recent progress in these areas including: (i) synthesis and characterization of ionically conductive, mechanically robust poly(ethylene oxide) (PEO)-based membranes and (ii) development of a 2 V sodium polysulfide/biphenyl full cell which exhibits a stable capacity ~170 mAh/gNa2S8 over 150 cycles.

Phenazine-Based Anolyte Materials in Aqueous Redox Flow Batteries
Aaron Hollas, Pacific Northwest National Laboratory

The high cost of vanadium-based redox flow battery systems has spurred interest in low cost redox-active organics as potential candidates to replace vanadium. We have previously reported 10 cm2 cell data on the phenazine-based anolyte DHPS (7,8-dihydroxyphenazine-2-sulfonic acid) coupled with the ferrocyanide catholyte. Demonstration of the phenazine system at cell sizes up to 200 cm2 will be presented along with preliminary cost modeling of this chemistry. New phenazine derivatives and their impact on system performance will also be described.

Capacity fade with aqueous-soluble organics: its measurement, minimization, and reversal.
Michael Aziz, Harvard University

In the study of redox-active aqueous-soluble organics: We have developed the most accurate way yet for measuring low capacity fade rates of molecular electrolytes. We have developed an aqueous-soluble organic negolyte, called DPPEAQ, that breaks the record for the lowest full-cell capacity fade rate per day and per cycle, in the absence of rebalancing processes, among all flow batteries for which results have been published. We have determined the decomposition mechanism of an alkaline-soluble organic, DHAQ, that is known to be inexpensive at mass-production scale. We have developed one strategy, State-of-Charge limitation, that cuts the fade rate by a factor of 40. We have developed a second strategy, atmospheric O2 exposure, that has been demonstrated to recover 70% of lost capacity by oxygenating the decomposition product and thereby converting it back into DHAQ. In the study of porous electrodes, we have utilized the different optical fluorescence spectra of oxidized and reduced forms of a quinone in order to map state-of-charge at sub-pore scales. We have combined this with velocity-field measurements, using ~1 um fluorescent tracer particles, to map out the mass transport coefficient in several commercial carbons at several flow rates.

Predicting functionality and resiliency of aqueous organic redox flow battery
Vijay Murugesan, Pacific Northwest National Laboratory

Building a functional organic based redox active molecule can accelerate redox flow battery (RFB) design and deployment. Both intrinsic and emerging properties of redox active molecules dictates many critical requirements for RFB deployment such as affordability, long term stability and resiliency. For example, intrinsic solubility and intra-molecular interactions within electrolyte constituents will determine the energy density and long-term chemical stability respectively. Our multimodal spectroscopic and computational studies help us to analyze the organic redox molecular structure – property correlation and lead us prediction of optimal electrolyte design concepts.

Low Temperature Molten Sodium Halide Batteries

Erik Spoerke, Sandia National Laboratories

Molten sodium halide batteries are promising candidates for safe, low cost, scalable electrical energy storage. Traditionally high operating temperatures near 300°C, however, result in higher costs and potentially reduced lifetimes, resulting in limited widespread adoption for grid-scale applications. This program utilizes a non-traditional Na-NaI molten sodium halide chemistry that allows for reduced operating temperatures near 100°C. Our research has focused on developing materials solutions that address unique low temperature-dependent challenges to separator interfacial wetting, catholyte phase behavior and electrochemistry, and current collector performance. Recent technical advances have enabled dramatic improvements in battery performance consistency and electrochemical cycling at temperatures near 100°C, unlocking the potential to realize this new class of low temperature molten sodium batteries.

Component Research for Redox Flow Batteries and Open Batteries

Tom Zawodzinski, Oak Ridge National Laboratory

In open battery systems such as flow batteries, the performance of components is critical to achieving high performance. Based on the premise that the same underlying principles govern the behavior of all similar types of materials used in similar processes, this project studies a series of aspects of archetypal membranes and electrodes used in systems ranging from aqueous flow batteries to non-aqueous flow batteries to Zn-based batteries. Partly in collaboration with other national labs, we have developed new tests of component performance (Zn cross-over and porous electrode performance) and durability (aqueous organics). We have elucidated the coupled electrochemistry and chemistry of Zn electrodes and we have discovered a new path to lowering cross-over while maintaining conductivity in non-aqueous electrolytes. Using a design framework developed this year, these findings will be implemented in scaled-up cells connected to the ORNL microgrid interface system.

Battery Systems Based on Naturally Abundant, Low Cost Materials

Amy Marschilok, Stony Brook University
Esther Takeuchi, Stony Brook University
Kenneth Takeuchi, Stony Brook University

When envisioning scale up in the number and size of batteries produced to address new applications such as grid level energy storage and energy storage coupled with renewable energy sources (solar, wind, etc.), a big limitation is supply and cost of electroactive materials. The predominant metals used in modern batteries are available in limited quantities from narrow geographic locations. For example, the portable lithium ion battery technology which dominates today's rechargeable (secondary) battery market is based on cobalt (Co) containing energy storage (cathode) materials and lithium (Li) containing ion shuttles (anode and electrolyte). The project focuses on transition metal based redox centers with significantly higher specific earth abundance than cobalt and mobile cations with greater abundance than lithium. Progress on the development and investigation of these systems will be described.

Advanced Membranes for Flow Batteries: Anion Exchange Membranes

Cy Fujimoto, Sandia National Laboratories

Membranes play an important role in flow batteries since battery efficiency and capacity retention properties are tied to membrane conductivity and selectivity. Although, vanadium redox flow batteries are being demonstrated at grid scale, raw material cost concerns are driving R&D to "alternative" flow battery chemistries in aqueous organic and non aqueous flow batteries. These "alternative" flow batteries require alkaline stable anion exchange membranes that are not commercially available. This presentation discusses Sandia's anion exchange membrane and how it compares against other competitor membranes and our membrane development for aqueous organic and non aqueous flow batteries.

Understanding the Mechanical Behavior of Materials for Electrochemical Energy Storage
Yang-Tse Cheng, University of Kentucky

Mechanical behavior of materials can strongly affect the performance and durability of electrochemical energy storage systems. For example, fracture and delamination events can occur during repeated charging and discharging operations due to diffusion-induced stresses and thermal stresses. An improved understanding of the mechanical behavior of electrode materials and electrode/electrolyte interfaces, which often evolves with the state-of-charge and cycle number, is therefore necessary for improving the performance and durability electrochemical energy storage systems. In this presentation, I will provide an overview of our recent work on using three complementary measurement techniques: (1) in situ electrochemical nanoindentation, (2) peel adhesion and cohesion test, and (3) electrode curvature measurement to help understand the relationships between the mechanical behavior of materials and the performance and durability of high capacity electrodes. Examples include silicon/polymer porous composite electrodes, lithium metal electrodes, polymer –ceramic composite electrolytes, and ceramic solid electrolytes. These in situ and ex situ characterization techniques may also be used to investigate the coupled electrochemical-mechanical behavior of a wide range of electrochemical energy storage materials under realistic working conditions.

Investigation of Intermediate-Temperature Na-Metal Halide (Na-MH) Batteries and Large Cell Demonstration
Guosheng Li, Pacific Northwest National Laboratory

Due to the use of the naturally abundant element - sodium (Na) - as a charge carrier, Na-metal halide (Na-MH) batteries have great benefits, which can reduce material costs and enable the market penetration in energy storage system applications. We carried out extensive studies to understand the fundamental anion chemistry of Na-MH batteries by replacing NaCl with NaI and NaCl, respectively, and explored its underlying reaction mechanism in detail through various structural characterization and electrochemical techniques. In order to further reduce the material cost of Na-MH battery technology, Fe cathodes are studied to replace the Ni cathodes used in current Na-MH batteries. Preliminary results indicate that the Fe cathode can exhibit superior battery performance compared to the current Ni cathodes. A new large cell architecture with an improved anode design is also tested to demonstrate a planar Na-MH battery with a considerably large capacity.

Development of high-performance Na-ion battery with layered transitional metal oxide cathodes
Xiaolin Li, Pacific Northwest National Laboratory

Na-ion battery is a low cost and high efficiency energy storage technology for improving the grid reliability and resiliency. The overall goal of the program is to develop Na-ion batteries with close or comparable performance to Li-ion batteries but lower cost. This year the focus has been on the development of high capacity layered transition metal oxide cathode materials, understand the fading mechanisms, and demonstration at a close to practical testing conditions.

Power Electronics

Development of the Sandia Advanced Power Electronic Conversion Systems Laboratory
Jacob Mueller, Sandia National Laboratories

The Sandia Advanced Power Electronic Conversion Systems (APEX) laboratory is a new facility dedicated to the development of advanced hardware topologies and intelligent control strategies for utility-scale energy storage applications. Over the past year, the lab's capabilities have been crafted to meet the research challenges of next-generation grid-tied storage systems. The lab is driven by a system integration perspective on power conversion research and is designed to cut across traditionally separate disciplines. This interdisciplinary approach links the diverse portfolio of projects within the power electronics thrust area and strategically positions the lab to address the complex challenges of real-world grid storage.

Smart GaN-based Inverters for Grid-tied Energy Storage Systems
Medhi Ferdowsi, Innocit

InnoCit is developing a modular smart GaN-based inverter (Ganverter) for the integration of battery systems into industrial/residential 480Vac grids. InnoCit's solutions offer a bidirectional transfer of 20kW between a 900Vdc battery rack and a 3-phase 480Vac grid in 3U rack chassis. Up to 10

Ganverters can be paralleled to achieve power levels of up to 200kW. InnoCit has successfully developed and tested the deliverables of its Phase II project and is currently working towards the final enclosure design and commercialization of the Ganverter. The aim of this Phase IIB is to achieve a TRL 8 status with all the required certifications completed and to have the commercialization started during this Phase IIB project.

Low Voltage and High Current Bidirectional Converter for Grid-tied Flow Battery Energy Storage System
Alex Huang, UT Austin

Battery system such as Lithium ion battery or flow battery typically has low voltage. To interface this with higher voltage systems such as power grid and EV drive train, stacking the battery to higher voltages are needed. The challenge is complicated voltage balancing and BMS system. This issue can be addressed if a low voltage and high current bidirectional grid connected converter can be developed and interface with the flow battery. The project objective is to develop an advanced 48Vdc to 480Vac grid connected bidirectional battery interface.

High Frequency Link Converters using Advanced Magnetics
Todd Monson, Sandia National Laboratories

High frequency DC links, utilizing advanced magnetic materials, are an enabling technology for transportable energy storage and power conversion systems. Compact and agile systems, able to fit inside a single semi-trailer, will significantly decrease the cost and time to install solar, wind, and geothermal energy systems in even the most remote locations. To accomplish this goal, new advanced magnetic core materials that can perform at high frequencies without active cooling are being fabricated. The g' phase of iron nitride, manufactured into magnetic components for the first time ever, will lead to lighter, smaller, more affordable, and higher efficiency transformers required for transportable energy storage systems and the widespread adoption of renewable energy. The fabrication of iron nitride and iron nitride based composite magnetic components using innovative manufacturing techniques will be discussed.

Medium-voltage Power Electronics for Grid-tied Energy Storage
Kristin Booth, The Ohio State University

Research on wide bandgap (WBG) semiconductors has revealed that Silicon Carbide (SiC)-based systems have better performance when used in high voltage, high temperature, and high frequency conditions than Silicon (Si)-based systems. The team from Ohio State University is evaluating SiC devices to build a SiC MOSFET-based medium-voltage power converter for a grid-tied energy storage system. In the first project year, the team has designed and fabricated a gate driver rated at 6.5 kV with theoretical common mode transient immunity of 200 kV/μs and a 10 W self-sustaining auxiliary power supply which can charge the gate driver from a 4.5 kV DC bus. The static evaluation, double pulse test, and short circuit test for the GeneSiC 3.3 kV SiC MOSFETs were completed. The test results show satisfactory performance regarding on resistance, switching loss, and short circuit sustaining time. Future work includes 6.5 kV SiC discrete device evaluations and power module fabrication. After finishing the comprehensive evaluations, a DC-DC converter based on the 6.5 kV devices will be implemented.

GLIDES: Delivering Efficient, Flexible Energy Storage
Ayyoub Momen, Oak Ridge National Laboratory

Ground Level Integrated Diverse Energy Storage (GLIDES) is modular, low-cost energy storage technology that was invented and demonstrated at Oak Ridge National Laboratory (ORNL). GLIDES stores energy by compressing gas using liquid piston inside high-pressure reservoirs. Prototype measured data, as well as the thermodynamic analysis, suggest this transformative technology will provide a round trip efficiency of 70-82% at a storage cost of <$180-400/kWh [1] current research focuses on readying the technology for deployment by developing grid integration interface and characterizing its power generation.

Realibity

Reliability Testing of Li-ion Batteries for Stationary Applications
Daiwon Choi, Pacific Northwest National Laboratory

To increase the utilization of intermittent renewable energy resources, cost effective, safe and long cycle life electrochemical energy storage is required. Therefore, various types of lithium-ion batteries are currently deployed for stationary energy storage applications due to high voltage, energy density, and long cycle life. However, state-of-the-art lithium-ion battery performance as a stationary energy storage is not well explored and understood compared to vehicle application in terms of reliability. In this work, four different Li-ion battery chemistries including NCA and LFP type cells are subjected to grid duty cycles specified to frequency regulation and peak shaving services. Our test setup, protocol and updated results will be compared and discussed.

In-situ Reliability Studies of Vanadium Redox Flow Batteries: High Voltage Stressors
Rajankumar Patel, Pacific Northwest National Laboratory

Vanadium Redox flow batteries (VRFBs) have been gaining momentum in industry due to their relatively low capital and cycle cost in comparison with other energy storage technologies and their ability to efficiently store large amounts of electrical energy. VRFBs are considered durable systems with an expected decade long lifetime, equivalent of several thousand cycles; however, degradation mechanisms of the system components have thus far been scattered or scarcely addressed. In this study, several accelerated stress tests have been designed to identify probable degradation mechanisms and to eventually develop models for aging prediction that can help reduce the duration and cost associated with real lifetime tests. This is the first installment of this stress tests: High Voltage. VRFB usually operates with voltage limits to 1.55-1.65 V due to the electrode corrosion and oxygen evolution in the catholyte. High cutoff voltage may be considered as a stressor accelerating the VRFB cell and component degradation. Our in-situ reliability study of VRFBs, tested for the 1.6 V – 1.8 V at 80mA/cm2 for 500 charge/discharge cycles, uncovered that high voltage of 1.75 V to be the upper limit for charging without any significant component degradation. Stressors aid in aging prediction which is essential to estimate the overall lifetime and the cost of a battery system.

Durability and Reliability of Commercial Lithium-Ion Cells as a Function of Chemistry and Cycling Conditions
Yuliya Preger, Sandia National Laboratories

Energy storage systems (ESS) utilizing Li-ion batteries are increasingly deployed to maintain a robust and resilient grid and facilitate the integration of renewable energy resources. To ensure long-term system safety and reliability, batteries must be selected based on application specific requirements and performance characteristics. However, suitable cell selection is made difficult by the dearth of data comparing popular commercial chemistries under comparable operating conditions. To address this gap, we initiated a large-scale, multi-year aging study of commercial $LiFePO_4$/LFP, $LiNi_xCo_yAl_{1-x-y}O_2$/NCA, and $LiNi_{0.80}Mn_{0.15}Co_{0.05}O_2$/NMC cells, varying the discharge rate, depth of discharge (DoD), and environment temperature. Though all cells were cycled within manufacturer specifications, the time to reach 80% capacity varied by thousands of hours and cycle counts among cells of different chemistries and cycling conditions. The degradation of cells in this study was compared to that of similar commercial cells in previous studies to identify universal trends and to provide a standard deviation for performance. The breadth of data collected in this study, and an ongoing calendar aging study, lays the foundation for a comprehensive evaluation of the applicability of various popular battery degradation models, many of which were previously evaluated against limited datasets.

Multi-scale Thermal Stability Study of Lithium-ion Batteries as a Function of Chemistry and State of Charge
Yuliya Preger, Sandia National Laboratories

Uncertainty about energy storage with respect to safety and reliability is a barrier for deployment, especially in the case of occupied buildings and other behind the meter applications. The safety of lithium-ion batteries is primarily quantified by thermal runaway characteristics such as onset temperature, peak heating rate (HR), and maximum pressure release. This research takes a critical look at the materials aspects of thermal runaway of lithium-ion batteries and correlates contributions from individual cell components to thermal runaway trends. An accelerating rate calorimeter (ARC) was used to evaluate commercial lithium-ion cells based on $LiCoO_2$ (LCO), $LiFePO_4$ (LFP), and $LiNi_xCo_yAl_{1-x-y}O_2$ (NCA) at various states of charge (SOC). Cells were disassembled and the component properties were evaluated by thermogravimetric analysis (TGA), differential scanning calorimetry (DSC), and temperature-resolved X-ray diffraction (TR-XRD). This systematic evaluation of component to whole cell degradation provides a scientific basis for future thermal modeling and design of safer cells.

Reliability Test Laboratory Update

David Reed, Pacific Northwest National Laboratory

The Reliability Test Laboratory at PNNL was created to accelerate to the development and deployment of energy storage into the electric infrastructure. Reliability testing is critical for increased acceptance of the technology; the performance and lifetime of storage systems under grid duty cycles should be quantified throughout the industry and used to direct research related to degradation and aging of the technology. This poster will describe the construction and various types of energy storage technologies being tested; preliminary results of some technologies under grid duty cycles will also be presented.

Battery Management System Standards

David Rosewater, Sandia National Laboratories

Well-designed battery management is critical for the safety and longevity of batteries in stationary applications. This document is intended to inform battery system designers and integrators in the challenges to battery management design. This document assists in the selection between design options by supplying the pros and cons of a range of technical solutions. Many aspects of battery management design require integration with other systems such as energy management or charge control systems. System integration can be made difficult or impossible without a minimal level of communication interface and control interface standardization. To address this issue, this document offers recommendations and best practices for interface design to streamline system integration.

Energy Storage Models for Risk Optimization

David Rosewater, Sandia National Laboratories
Ross Baldick, University of Texas at Austin
Surya Santoso, University of Texas at Austin

When batteries supply behind-the-meter services such as arbitrage or peak load management, an optimal controller can be designed to minimize the total electric bill. The limitations of the batteries, such as on voltage or state-of-charge, are represented in the model used to forecast the system's state dynamics. Control model inaccuracy can lead to an optimistic shortfall, where the achievable schedule will be costlier than the schedule derived using the model. To improve control performance and avoid optimistic shortfall, we develop a novel methodology for high performance, risk-averse battery energy storage controller design. Our method is based on two contributions. First, the application of a more accurate, but non-convex, battery system model is enabled by calculating upper and lower bounds on the globally optimal control solution. Second, the battery model is then modified to consistently underestimate capacity by a statistically selected margin, thereby hedging its control decisions against normal variations in battery system performance. The proposed model predictive controller, developed using this methodology, performs better and is more robust than the state-of-the-art approach, achieving lower bills for energy customers and being less susceptible to optimistic shortfall.

Heat Release from Thermal Decomposition of Layered Metal Oxide Cathodes in Lithium-Ion Batteries
Randy Shurtz, Sandia National Laboratories

Existing models of thermal runaway in lithium-ion batteries rely heavily on calorimetry measurements of battery components. While these methods are essential to calibrate model parameters that define chemical reaction rates, there are disadvantages to fully-empirical approaches when they are also used to define heats of reaction. This study examines various proposed decomposition schemes relevant to layered metal oxide cathodes and identifies the most plausible reaction pathways through comparison to the available species measurements and by comparing the thermodynamic heat release for the individual reaction steps to calorimetry measurements. Several modeling advantages emerge from this approach. First, reliance on both species data and consistency with thermodynamic heat release provides more information to identify the specific chemical transformations occurring. Eventually, this may include the ability to identify and explain variation in the extent of electrolyte oxidation based on experimental conditions. Second, uncertainties associated with total heat release measurements can be reduced through identification of an appropriate thermodynamic heat release. Likewise, heat release uncertainty can be deconvoluted from uncertainty associated with chemical reaction rates. Third, keeping thermal runaway models up-to-date becomes easier if fewer parameters need to be re-optimized when new materials are implemented in lithium-ion batteries. As the thermodynamic parameters governing heat release become well-understood, trends in the kinetic parameters can be identified and correlated so that safety predictions can be made for new material formulations a priori. These methods lead to thermal runaway models with better physics and improved predictive capabilities.

Analytics

Distributed Controls Using Energy Storage for Improved Grid Stability and Resilience
Roghieh Biroon, Clemson University

This poster presentation will illustrate the modeling, simulation, and control algorithm design methodology needed to develop and ultimately deploy a distributed controls strategy using energy storage for improved power grid stability and resilience. A distributed approach to power grid controls development has the potential to improve the effectiveness and coverage achievable in wide-area controls and increase the robustness to failure of any one actuator than is possible in a centralized strategy. Energy storage systems are excellent candidates to implement this distributed strategy because they are a more generic all-purpose type of power injection device than other energy resources can deliver. Energy storage can absorb and discharge active power as well as provide reactive power to the grid with very fast response times. The control strategy presented here will harness these features to improve small signal and transient stability, which will lead to a more resilient power grid.

Utilization of Existing Generation Fleet Using Large Scale Energy Storage Systems
Tu Nguyen, Sandia National Laboratories

In this work we propose an optimization approach to evaluate the benefit of large-scale energy storage system (ESS) for utilizing an existing generation fleet that often operates at suboptimal working conditions due to peaky nature of the load. The objective is to find the optimal schedule for thermal units and the ESS that minimizes the daily system operating cost. This cost is the sum of the fuel cost, variable O&M cost and start-up cost of all thermal units. Case studies are conducted to evaluate the operating cost savings by using ESSs for a utility company in Alaska.

Energy Storage Planning for Clean Energy Target
Tu Nguyen, Sandia National Laboratories

More utilities, energy providers, and governments are considering the transition to 100% renewable generation or at least carbon-free generation. In this work, we propose an optimization approach to analyze the amount of renewable generation and energy storage required to make such a transition. Specifically, given locations of renewable generation, we solve an optimization problem to find the amount of solar PV and wind resources that should be located at each site and to find the power rating and energy capacity of energy storage required to balance 100% of a utility's demand. We investigate the use of this optimization approach for case studies using multiple years of historical meteorological data and demand data from a medium-sized utility in New Mexico, USA that accounts for the majority of the demand in the state. The results show the minimum amount of solar PV and wind generation at each location as well as energy storage power and energy requirements, needed to balance the utility's demand and renewable generation.

A Model Predictive Frequency Control of Low Inertia Microgrids with Energy Storage Systems
Reinaldo Tonkoski, South Dakota State University

In isolated power systems with low rotational inertia, fast-frequency control strategies are required to maintain frequency stability. Considering the limited resources, the control strategies must provide the flexibility to handle operational constraints so that the controller is optimal from a technical as well as an economical point-of-view. A model predictive controller (MPC) for energy storage systems is proposed which can provide fast-frequency control. Given a simple-predictive model of the system, MPC computes control actions by solving a finite-horizon, online optimization problem that satisfies peak power output and ramp-rate constraints. Simulation results demonstrate that through proper selection of controller parameters, desired frequency dynamics can be achieved.

Opportunities for energy storage plus solar in CAISO
Raymond Byrne, Sandia National Laboratories

California has many opportunities for energy storage, including a state mandate to increase the amount of deployed storage. This research looks at the opportunity to pair energy storage with solar in the California Independent System Operator (CAISO) market. Using historical market data for ~2300 nodes in CAISO, the maximum potential revenue for solar, as well as solar plus storage, was evaluated using several years of historical market data. The initial analysis focused on participating in the day-ahead market. Future work will incorporate the real-time energy market, frequency regulation, as well as the flexible ramping product.

Siting Energy Storage for Resilient Distribution Systems
Randy Brost, Sandia National Lab

Natural or man-made disasters can have a significant impact on individuals, families, and society as a whole. A significant contributing factor is disruption to the electrical system. For significant disasters, power can be interrupted for weeks or even months in some areas. In this work, we study the problem of how to equip a feeder distribution system with energy storage and other components to aid resilience and reduce societal impact during a disaster. We explore the application of semantic graph representations, exploiting their capability to represent and analyze information spanning multiple domains (such as societal benefit, electricity model information, geospatial factors, existing and potential infrastructure options, etc), and also their ability to identify incisive toplogical constraints to reduce the size of the problem space. We report an initial implemented algorithm demonstrating these capabilities on a multi-faceted example.

Continuous-time Look-Ahead Scheduling of Energy Storage in Real-time Markets
Bosong Li, University of Utah
Masood Parvania, University of Utah

This poster presents a continuous-time look-ahead optimization model to schedule balancing and regulation services for energy storage (ES) systems in real-time markets. The proposed model co-optimized the services provided by the ES systems and generating units to minimize the total real-time system operation cost using the receding horizon control approach. Over each control horizon, the real-time load trajectory is forecasted and updated using a continuous-time Gaussian process. The continuous-time problem is projected to a finite-dimensional function space spanned by Bernstein polynomials and converted into a solvable mixed integer linear programming problem.

Materials II

Electrochemical Energy Storage through Ligand-Based Charge Manipulation
Mitchell Anstey, Davidson College

Public and private investments in energy storage have created a 100 billion dollar industry, and this industry is now converging on grid-scale applications due to the urgent need for resource conservation and our ever-increasing global demand for energy. Redox flow batteries (RFBs) are one method for grid-scale energy storage, being used for peak-shaving and renewable energy incorporation into the grid. Our lab has been exploring the ability of molecular structure to influence electrolyte performance metrics such as Coulombic Efficiency, charge-recharge cycling, and voltage window. This poster will describe the work in our lab that focuses on molecular design to address these specific issues in nonaqueous redox flow battery electrolytes.

Radialene Radicals for Aqueous Redox Flow Batteries
Christopher Bejger, The University of North Carolina at Charlotte

Aqueous organic redox flow batteries (RFBs) are becoming more economically feasible and are expected to surpass vanadium-based energy storage systems during the next decade, in terms of cost/kilowatt hour. There are, however, few organic species capable of acting as charge storage species for aqueous RFBs. We aim to develop aqueous organic RFBs comprising persistent, soluble, radialene redox couples. This year our group has developed a synthetic strategy for increasing the solubility and stability of hexa-substituted[3] radialenes. We have found that desymmetrization and the addition of hydrophilic appendages increases solubility while limiting unfavorable aggregation. This results in better capacity retention during extended cycling in laboratory scale devices.

Advanced Membranes for Flow Batteries: Anion Exchange Membranes
Cy Fujimoto, Sandia National Laboratories

Membranes play an important role in flow batteries since battery efficiency and capacity retention properties are tied to membrane conductivity and selectivity. Although, vanadium redox flow batteries are being demonstrated at grid scale, raw material cost concerns are driving R&D to "alternative" flow battery chemistries in aqueous organic and non aqueous flow batteries. These "alternative" flow batteries require alkaline stable anion exchange membranes that are not commercially available. This presentation discusses Sandia's anion exchange membrane and how it compares against other competitor membranes and our membrane development for aqueous organic and non aqueous flow batteries.

Materials and Membranes for High Energy Density Non-Aqueous Redox Flow Batteries
Jagjit Nanda, Oak Ridge National Laboratory

Redox flow batteries (RFBs) are promising energy storage devices for grid-level applications due to their long cycle life and the ability to independently scale their energy and power densities. To enable widespread adoption of nonaqueous RFBs, high energy density anolyte/catholyte systems and low-cost polymeric membranes which prevent crossover of redox-active species are required. This presentation will describe our recent progress in these areas including: (i) synthesis and characterization of ionically conductive, mechanically robust poly(ethylene oxide) (PEO)-based membranes and (ii) development of a 2 V sodium polysulfide/biphenyl full cell which exhibits a stable capacity ~170 mAh/gNa2S8 over 150 cycles.

Next Generation Cell design and Material Optimization for Sodium Batteries
Stephen Percival, Sandia National Laboratories

Optimization of our sodium battery testing platform is a key development to enable high throughput and reliable testing of emerging sodium battery technologies. Cell optimization includes new cell designs, improved cell sealing, and identification of compatible materials for cell construction. Recent developments in glass electrode sealing and cell geometry have eliminated several major points of failure in previous battery cell prototypes and facilitates sodium and salt interaction with the NaSICON sodium ion conductor. In addition, new, compatible polymer seals at separator interfaces have increased cell lifetimes significantly. Finally, identifying the "right" compatibility of NaSICON and sodium anodes improves this critical interface and reveals the importance of physical and electrochemical interactions between the anode and the solid state separator. Effective improvements in cell design and materials performance have established a platform for improved battery reliability and prototype evaluation, key to the development of new sodium battery technologies.

Solid State Separator Development for Sodium-Based Batteries
Amanda Peretti, Sandia National Laboratories

The promise of molten sodium-halide batteries depends significantly on the performance of solid state separators that allow facile sodium ion conduction while physically and electrically isolating the molten sodium anode from the molten salt catholyte. Our program is focused on the development of molten sodium batteries that operate much below traditional values near 300°C, which challenges the temperature-dependent conductivity of these materials. We are actively working to develop solid state ceramic and composite separators that will perform effectively at these reduced temperatures. Our research has emphasized the efficient synthesis of NaSICON ceramic separators and demonstrated their utilization in lab-scale battery testing. In addition, we have explored a number of alternative ion conductive materials, including bulk composites and bio-inspired highly organized 2D material composites, evaluating their viability for application in the chemically challenging environments of a sodium-halide battery. These emerging separators not only stand to improve molten sodium battery performance, but potentially alternative battery chemistries that would benefit from highly conductive zero-crossover separators.

Materials and Membranes for High Energy Density Non-Aqueous Redox Flow Batteries
Ethan Self, Oak Ridge National Laboratory

Redox flow batteries (RFBs) are promising energy storage devices for grid-level applications due to their long cycle life and the ability to independently scale their energy and power densities. To enable widespread adoption of nonaqueous RFBs, high energy density anolyte/catholyte systems and low-cost polymeric membranes which prevent crossover of redox-active species are required. This presentation will describe our recent progress in these areas including: (i) synthesis and characterization of ionically conductive, mechanically robust poly(ethylene oxide) (PEO)-based membranes and (ii) development of a 2 V sodium polysulfide/biphenyl full cell which exhibits a stable capacity ~170 mAh/gNa2S8 over 150 cycles.

Elucidating Molecular Transport through Membranes in Flow Batteries
Leo Small, Sandia National Laboratories

Redox flow batteries are a promising technology for grid scale energy storage. This year we successfully elucidated mechanisms of transport in membranes for low cost aqueous-organic flow batteries and leveraged an OE-sponsored workshop to translate this knowledge to nonaqueous systems that offer higher voltages for more energy dense systems. We have sponsored several university collaborators who have developed new models and promising tunable materials for flow batteries. In all, we have developed a clearer understanding of the foundation of flow batteries: the interplay between solvent, salt, and membrane.

Development of Sulfide based solid state Electrolytes for Na-ion Batteries
Donghai Wang, Pacific Northwest National Laboratory

Sulfide-based solid-state electrolytes (SSEs) are safer alternative to common organic electrolytes with high operational voltage and similar ionic conductivity for Na-ion batteries. Hydrolysis of the sulfide-based electrolytes and subsequent release of a hazardous hydrogen sulfide when exposed to moisture pose major concern in using the sulfide-based SSEs. This year the focus has been on improving the chemical stability of the sulfide-based SSE of low cost Na3PS4. We used an anionic N-doping approach to develop a new SSE of Na3PS4-xN2/3x ($0 \leq x \leq 0.8$), evaluated its conductivities at different chemical conditions, and identified the optimized composition with improved stability.

Lithium-Pretreated Hard Carbon as High-Performance Sodium-ion Battery Anodes
Biwei Xiao, Pacific Northwest National Laboratory

Hard carbon (HC) is the state-of-the-art anode material for sodium-ion batteries. However, its performance has been plagued by the limited initial Coulombic efficiency (ICE) and mediocre rate performance. Here, we used an electrolyte based on tetraglyme combined with a pre-lithiaton technique to boost the ICE to >92% with ~220 mAh/g capacity. This approach leads to a full cell with doubled capacity when coupled with Na3V2(PO4)3. This work provides new perception on the anode development for SIBs.

Monitoring the State-of-Charge of a Vanadium Redox Flow Battery with the Acoustic Attenuation Coefficient: An In Operando Noninvasive Method
Xiaoqin Zang, Pacific Northwest National Laboratory

Redox flow battery technology has been increasingly recognized as a promising option for large-scale grid energy storage. Access to the health status of the electrolyte is vital to maintaining optimal and economical battery operation. An ultrasonic probing approach is designed to monitor the state-of-charge of vanadium redox flow battery online noninvasively. The state of charge estimated from the acoustic attenuation coefficient is found to be robust to temperature variation.

Regenerated hydrogen-iron flow cell for low-cost distributed long-duration energy storage
Litao Yan, Pacific Northwest National Laboratory

Redox flow batteries (RFBs) are currently the resurgence of interest for energy storage since it can provide some critical services in many grid energy application, e.g. premium back-up power, balancing daily energy time shift and improving grid reliability. Hydrogen metal (e.g. iron and vanadium) flow cells are gaining extensive attention because of their fast reversible kinetics, excellent performance and low-cost reactant materials. Recently, we demonstrated a high reversible capacity hydrogen iron flow battery with the assistance of water management. Long-duration energy storage (10-200 hours) will build on our hydrogen iron flow cell due to the compressibility of the hydrogen and the low-cost and earth abundance active materials.

Power Electronics

X7R Ceramic Capacitor Lifetime For Pesudo-DC-Link Topologies
Jonathan Bock, Sandia National Laboratories

Class II ceramic capacitors with X7R specification (BaTiO3-based compositions) often have limited DC lifetime under elevated temperatures and high electrical fields. The limited lifetime is caused by degradation of the capacitor's insulation resistance under DC lifetime. This degradation is a critical limitation for high-reliability applications, and also limits energy density of capacitors by requiring a significant de-rating in voltage for reliable use. This degradation is caused by electromigration of charged defects in the dielectric piling up at the cathode, and – if the degradation stays below a specific threshold – is should be partially reversible by reverse biasing. Initial accelerated lifetime testing for X7R ceramic capacitors was completed to show the lifetime extension under slow bipolar AC cycling which paves the way for potential pseudo-DC link capacitor technologies that 'heal' capacitor DC links to increase reliability of future systems.

Design and Fabrication of High-Temperature Optocoupler For High-Density Power Module
Zhong Chen, University of Arkansas

A high-temperature optocoupler is being designed and fabricated to replace isolation transforms as the galvanic isolation solution for the 3D integration of high-density power modules. The proposed optocoupler delivers a continuous operation at 250oC with a lifetime of 10 years. Optical and electrical studies were conducted on gallium nitride (GaN), and silicon carbide (SiC) based optoelectronics materials and devices at elevated temperatures (~550oC). Low temperature co-fired ceramic (LTCC) based optocoupler packaging is designed and fabricated to accommodate LEDs and photodetectors. The discrete optocouplers fabricated from LTCC are integrated to the gate driver circuitry of the high-density power module and tested at elevated temperatures.

Development of a Battery Chemistry Agnostic Secondary Use Energy Storage System
Madhu Chinthavali, Oak Ridge National Laboratory

Secondary-use energy storage technologies come in a variety of different chemistry and aged systems. For integration into large utility grade systems (at the scale of 100kW and higher), power electronic systems are needed that can intertie multiple dissimilar battery systems. This work demonstrates the development of a software and power electronic system for connection of multiple secondary-use systems. The initial demonstration consists of a hardware-in-the-loop simulation of the power electronic system within a OPAL-RT simulation environment coupled with digital signal processor controllers and communication network to optimize the dispatch of the energy storage systems. Future work will focus on the development and demonstration of a full-hardware implementation.

Residential Deployment of a Secondary Use Energy Storage System
Michael Starke, Oak Ridge National Laboratory

This project describes the final stage of a Grid Modernization Laboratory Call project focused on deploying a secondary-use energy storage with Habitat for Humanity. This work includes the development of a ORNL developed power electronics interface and software to support communications and control of a secondary-use energy storage technology developed by Spiers New Technologies. The energy storage system was deployed in May and is under evaluation. Example economic evaluation and demonstration of the closed loop control with communication systems is presented as part of this work. In the final stages, commercialization of the technology is in discussion with partners.

Extreme Solar: Towards 24-7 Renewable Energy
Valerio De Angelis, Urban Electric Power
Satish Ranade, New Mexico State University

The purpose of the Extreme Solar project is to build a solar panel integrated with rechargeable ZnMnO2 battery cells and connected to commercial solar micro-inverters. The batteries are charged from the solar panels and discharged during the evening or when additional power is needed. In FY19, two solar-battery systems were assembled and tested in NMSU and one in UEP. Findings from the installations and proposed improvements will be presented.

Advanced Gate Dielectrics for Wide-Bandgap Devices
Peter Dickens, Sandia National Laboratories

Due to the desire to design and operate power transistors at elevated temperatures, higher switching speeds, and higher voltages, wide-bandgap semiconductors are being thoroughly researched and developed for next generation power electronics. Among wide-bandgap semiconductors, SiC is positioned at the forefront owing to its manufacturability, high breakdown field, good thermal conductivity, and saturated electron velocity, though the current gate oxide performance limits device reliability. In this work, we will present our recent efforts in developing new high-k dielectrics for implementation with SiC. Gate oxide choices for SiC are limited due to low conduction band offsets and/or poor chemical and structural quality at the oxide|carbide interface. However, we will demonstrate that epitaxial, lattice-matched alloys of MgO and CaO are prime candidates for SiC gate dielectrics. We will present on the structural and electrical optimization of MgO/MgCaO crystal quality and growth mode by both molecular beam epitaxy and pulsed laser deposition.

Advanced Capacitors for Future Power Conversion System
Bruce Gnade, Southern Methodist University

Capacitors are critical for voltage source converter functionality. DC-link capacitors are known to have reliability issues. Therefore, the overall goal of this program is to improve the understanding of high voltage breakdown in high dielectric constant inorganic ceramic capacitors. This year the focus has been on improving the understanding of resistance degradation in BaTiO3 at elevated temperature, using single crystal BaTiO3 as a model system to understand the impact and control of oxygen vacancy migration to maximize the long-term reliability of high voltage inorganic multi-layer ceramic capacitors.

Wide Bandgap Power Electronics Reliability
Bob Kaplar, Sandia National Laboratories
Oleksiy Slobodyan, Sandia National Laboratories

Vertical GaN power semiconductor devices represent the next frontier in power electronics, but their reliability is largely unknown. As such, this work has examined the reliability of high-voltage vertical GaN pn diodes under electrical switching stress conditions designed to approximate operation in an operating power converter. Changes in the current-voltage characteristics of the diodes in both forward and reverse bias configurations have been observed to be a function of switching voltage. In order to understand the microscopic origin of these changes and thereby correlate atomic-scale material properties with the performance of the diodes in a power converter, defect spectroscopy measurements are underway and are being correlated with stress conditions and the electrical performance of the devices. This poster will present the experimental methodology as well as key results of these measurements.

Advanced Power Electronics for Grid Storage
Satish Ranade, New Mexico State University

This project investigates the potential benefits of processing energy at the unit level (battery, cell) with subsequent series-parallel connections. Potential benefits are overall improved the efficiency and improved safety and reliability through battery level monitoring. A bidirectional dc-dc converter to interface multiple 3.6V/1A cells, and cell-level power management has been demonstrated. Continuing research includes magnetics design, battery health monitoring, and multilevel inverter ac front end.

Connecting Alaska Remote Villages using Medium Voltage Intertie System
Mariko Shirazi, University of Alaska Fairbanks

The cost of generating electricity in hundreds of remote communities in Alaska can exceed one dollar per kWh due to high cost of delivering and storing diesel fuel and insufficient consumption to leverage economies of scale for generation. Interties between communities can mitigate this concern by allowing consolidation of operations and maintenance requirements, operation of larger and more efficient generators, and ability to to leverage renewable resources at one site to serve loads at another. Medium voltage direct current (MVDC) interties offer advantages over their alternating current (AC) counterparts including reduced losses, reduced voltage-drop, and ability to use cable-based transmission for burial or underwater vs. overhead installations. This effort has studied state-of-the-art and trends in MVDC converter topologies and overall MVDC network conversion architectures with an eye towards identifying most promising architecture and topologies for low power applications, and has identified manufacturers and costs of various components such as converters, switchgear, and cable. Future work will include switching-level controller hardware-in-the-loop (CHIL) simulations based on the selected network architecture and converter topologies.

Advanced Power Conversion Systems featuring SiC MOSFETs with In-Situ Restoration Capabilities
Ranbir Singh, GeneSiC Semiconductor

Progress on power electronics for Grid-tied Battery Energy Storage Systems (BESS) featuring: (a) newly developed monolithically integrated High Voltage SiC MOSFET-Schottky Diodes; (b) Intelligent Gate Drivers that provide in-situ monitoring and restoration capabilities; and (c) novel three level Neutral point clamping topology is presented. The voltage and current ratings of newly developed 1200 V, 20 A SiC Monolithically Integrated MOSFET-Diodes will be extended to 3300 V, 50 A ratings. The 800 V dc output of the battery system is interfaced with the 12.47 kV, 60 Hz, 3-phase medium voltage distribution grid using a Dual Active Bridge (DAB), followed by Active Front End Converter (AFEC) topology, which features Neutral Point Clamped topology to reduce filter requirements. Intelligent Gate drivers featuring current and voltage sense will provide low-stress operating conditions for the newly developed medium voltage MOSFET-Diodes. The use of ultra-fast, high voltage SiC MOSFET based devices will result in significant reduced losses for the overall system due to their high frequency switching capabilities at high voltages. This SBIR program will demonstrate an unprecedented advances in size, efficiency and functionality of energy storage systems.

Engineering Routes Towards Synthesis and Performance of Layered Oxide Cathode Materials for Sodium-ion Batteries
David Wood III, Oak Ridge National Laboratory

Sodium ion batteries offer a significant cost reduction, improved cycle life, and electrode performance over traditional Li-ion batteries which make them ideal for large scale grid storage applications. A novel method was developed to synthesize highly-crystalline P2-$Na_{2/3}Fe_{1/2}Mn_{1/2}O_2$ cathode with uniform particle size. Higher capacity of half cells was demonstrated for the P2 cathode synthesized by a new method comparing to the baseline sol-gel method. The Na-ion diffusion properties of the P2 material were investigated by the galvanostatic intermittent titration technique (GITT), and a higher Na-ion diffusion coefficient for the material synthesized by the new processing method was observed. A hard carbon anode, which can deliver 250 mAh/g capacity at C/10 in half cells, was used to fabricate sodium-ion full cells using the P2 cathode material synthesized by the new method. Full cell capacity and cycling performance was engineered by introducing a pre-sodiation method to the hard carbon anode before full cell assembly.

Predicting Reliability, Improving Safety and Resiliency in Grid Connected Battery Energy Storage Systems
Harish Sama Krishnamoorthy, University of Houston

Energy storage deployments will grow about 10-fold over the next 5 years to 160 GWhr. High string voltage needed in grid energy storage systems affects both the potential for shock and arc-flash/blast – which is a major concern at high penetration levels. Hence, the main objective of this project is to investigate modular, multilevel inverter topologies and reliability prediction techniques for grid connected battery energy storage systems (BESS) to improve flexibility as well as resiliency. As a first step, self – battery management system (BMS) and state of charge (SoC) balancing methods are being explored for battery/inverter modules interfaced to the grid. Further, the component-level remaining useful life (RUL) index for SiC-FET and Li-ion batteries will be evaluated, followed by the analytical prediction of system-level RUL for grid connected modular BESS systems.

Ground Level Integrated Diverse Energy Storage (GLIDES)
Ayyoub Momen

Ground Level Integrated Diverse Energy Storage (GLIDES) is a modular, low-cost, energy storage technology developed that was invented and demonstrated at Oak Ridge National Laboratory (ORNL). GLIDES stores energy by compressing gas using liquid piston inside high-pressure reservoirs. Prototype measured data, as well as the thermodynamic analysis, suggest this transformative technology will provide a round trip efficiency of 70-82% at a storage cost of <$180-400/kWh current research focuses on improving the technology for deployment by developing grid integration interface and characterizing its power generation.

Smart GaN-based Inverters for Grid-tied Energy Storage Systems
Medhi Ferdowsi

InnoCit is developing a modular smart GaN-based inverter (Ganverter) for the integration of battery systems into industrial/residential 480Vac grids. InnoCit's solutions offer a bidirectional transfer of 20kW between a 900Vdc battery rack and a 3-phase 480Vac grid in 3U rack chassis. Up to 10 Ganverters can be paralleled to achieve power levels of up to 200kW. InnoCit has successfully developed and tested the deliverables of its Phase II project and is currently working towards the final enclosure design and commercialization of the Ganverter. The aim of this Phase IIB is to achieve a TRL 8 status with all the required certifications completed and to have the commercialization started during this Phase IIB project.

Equitable Regulatory Environment

Planning Considerations for Energy Storage in Resilience Applications
Jeremy Twitchell, Pacific Northwest National Laboratory

A lack of metrics and enforceable standards creates significant planning and economic hurdles for energy resilience investments. Absent standards, planning objectives for what resilient assets should do cannot be readily identified, and assets cannot be compensating for providing resilience. This poster presents the findings of a recent report, which proposes a locational framework for resilience planning that defines resilience in terms of critical loads. By identifying specific loads and the resilience risks they face, then identifying local grid needs, projects can be designed to meet specific resilience goals when the grid is down and pay for themselves by providing valuable services when it is up. Energy storage, which can provide critical backup power as well as valuable grid services, is a key enabling technology in this framework.

Industry Acceptance

Energy Storage Control Capability Expansion at Portland General Electric's Salem Smart Power Center
Jan Alam, Pacific Northwest National Laboratory

The value proposition of energy storage systems (ESSs) is a key topic for creating and advancing its acceptance within the electric power sector, particularly for electric utilities. While energy storage as a technology is gaining popularity within the electric utility industry, its anticipated value streams are not fully understood, quantified, and demonstrated. Unavailability of suitable demonstration sites/projects, lack of a deep understanding of available economic opportunities, and deployment complexities associated with pursuing those opportunities are some of the reasons that complicate value demonstration processes. This poster reports a transformative project aimed at enhancing the control capabilities of a Portland General Electric (PGE) owned 5 MW/1.25 MWh ESS located in Salem, Oregon with the goal of achieving better techno-economic value.

Washington Clean Energy Fund Economics
Patrick Balducci, Pacific Northwest National Laboratory

The Washington Clean Energy Fund (CEF) provided $14.3 million in funding to three Washington-based utilities for the purchase of four battery energy storage systems (BESSs) with a total investment of $43 million. Pacific Northwest National Laboratory (PNNL) was engaged to evaluate the economic benefits of these systems to the utilities and the customers they serve. PNNL developed an extensive taxonomy for estimating the value of benefits realized through transmission, distribution, bulk energy, and ancillary services. PNNL then modeled the benefits of each of these use cases specific to each utility at each site. This presentation highlights the results of this economic analysis, which includes several innovations such as the evaluation of a broad set of use cases, non-linear performance of battery operations, the performance of BESS control systems, and the benefits of using the Modular Energy Storage Architecture.

Modeling the Nantucket Energy Storage System
Vanshika Fotedar, Pacific Northwest National Laboratory
Xu Ma, Pacific Northwest National Laboratory

Nantucket Island is located off the coast of Massachusetts, and during summer months it may experience a temporary swell in the population (from 11,000 to over 50,000), which leads to a significant increase of energy demand. To meet this rise of demand and to improve reliability, National Grid plans to deploy a 6MW/48MWh Tesla lithium-ion battery energy storage system (BESS) with a new (10-16MW) combustion turbine generator (CTG) instead of building a third submarine cable for electricity transmission. The BESS and CTG not only produce considerable transmission deferral benefits but may also be profitable when participating in other services such as energy arbitrage, frequency regulation, and spinner reserve. In this work, PNNL models and optimizes the annual real-time operation of those devices and evaluates the economic benefits for both local and market services.

The BEAM Training Center at Santa Fe Community College
Stephen Gomez, Santa Fe Community College (SFCC)

Santa Fe Community College (SFCC) is an emerging leader in the implementation distributed energy generation, and in development and delivery of educational and training programs to prepare students for coming changes in the energy sector. SFCC is currently implementing the Building Energy Automation and Microgrid (BEAM) Training Center. BEAM will consist of two student training centers which, when combined, will offer the first community college energy curriculum capable of providing students with a comprehensive energy education from HVAC to microgrid control of energy supply. The first training center will be a B.E.S.T. Laboratory, which is a new program supported by the National Science Foundation. It consists of HVAC equipment and automation hardware and software. The second training center focuses on a new 12,000 ft2 greenhouse, powered by natural gas, solar PV, bio-fuels, and a Siemens microgrid controller. Support from NSF/NM-EPSCoR New Mexico SMART Grid Center is funding a faculty position to create a program to train students in installation, commissioning, data collection, and integration of clean energy assets and energy storage systems into operational microgrids. Once the greenhouse microgrid is operational it will serve as integral training tool in the BEAM Training Center, and it will provide DOE/Sandia operational access and data to support battery management system and energy management system research.

The Nanogrid at Santa Fe Community College
Stephen Gomez, Santa Fe Community College (SFCC), Sandia National Laboratory (SNL) and Siemens

Santa Fe Community College (SFCC), Sandia National Laboratory (SNL) and Siemens are leading the effort in the development, design, installation and commissioning of a microgrid system for the operation of a 12,000 ft2 aquaponics greenhouse (“the nanogrid”). The DOE-Office of Electricity provided partial funding and is managed by SNL in addition to support analysis of the existing grid, and provide technical project management support. The purpose of the energy storage project is to demonstrate resiliency in food production and perform peak shaving to reduce energy demand charges. It is the intention of this joint project to provide a permanent battery energy storage system (BESS) and to develop control algorithms that will optimize the operation of the BESS. This campus utilities will be operated and managed by a microgrid management system (MGMS) provided by Siemens to provide additional resiliency to the campus power grid. Phase I changes to the campus grid, electrical infrastructure, including BESS will operate the greenhouse. The BESS is a 100 kW / 85 kWh integrated lithium-ion battery system. The BESS installation is underway and the expected installation completion date is late November 2019. The nanogrid will eventually be integrated into the campus microgrid (a microgrid within a microgrid). SFCC shall also provide a framework to facilitate DOE-OE/SNL funding support for the project in the context of its energy storage test bed initiative.

Energy Storage Analysis for Regional Demonstrations Projects
Alexander Headley, Sandia National Laboratories

Sandia National Labs engages with a number of external entities to assess the value of energy storage systems in their situation and help them select appropriate parameters for proposal requests. Here, two such valuation studies with unique considerations are presented: community distributed solar generation in New York and the NELHA research campus in Hawaii. In NY, recent changes intended to incentivize proper timing and placement of distributed generation have increased the potential for energy storage in the area. The NELHA research campus could benefit from energy storage given a significant influx of photovoltaic generation, but upcoming operation of a large, potentially flexible hydrogen production facility would significantly affect the value proposition of energy storage in this case. General lessons learned from these and other valuation analyses will be presented.

Eugene Water and Electric Board / Korean Consortium Energy Storage Project
Kendall Mongird, Pacific Northwest National Laboratory

The Eugene Water and Electric Board (EWEB) / Korean Consortium Energy Storage Project is a multi-national initiative between EWEB and a group of Korean partners that will result in the deployment of three lithium-ion batteries totaling 1 MW/ 2 MWh at EWEB's Roosevelt Operations Center in Eugene, Oregon. Pacific Northwest National Laboratory was engaged by the U.S. Department of Energy to work with EWEB and the Korean partners in evaluating the economic performance of the energy storage system. Benefits include those associated with demand charge reduction, transmission charge reduction, capacity, demand response, energy imbalance market participation, and arbitrage. This poster presentation will provide an overview of the results of the EWEB / Korean Consortium Energy Storage Project economic assessment.

CESA State Energy Storage Policy Initiatives
Todd Olinsky-Paul, Clean Energy States Alliance (CESA)

Through the ESTAP program, CESA provides assistance to state energy agencies in developing energy storage policy, programs and regulations. This poster provides an overview of CESA's work in state policy and the outcomes of this work. States receiving CESA's policy assistance have included Connecticut, Massachusetts, Vermont, New Hampshire, Rhode Island, New Jersey, Minnesota, Washington State, New Mexico and others. Outcomes have included energy storage grant programs, incentive programs, regulatory reform, state roadmaps, and project deployment. This poster will show the connections between state policy, storage deployment, and market development.

Global Energy Storage Database (GESDB) Updates
Sam Roberts, Sandia National Laboratories

The DOE Global Energy Storage Database (GESDB) is a go-to source for unbiased, accurate, and up to date information on energy storage projects and policies. The free database, managed by Sandia National Laboratories, is publicly accessible and simple to use. The GESDB provides an open-access resource for detailed energy storage project technical characteristics and applications. This year the team worked to rebuild the database from the ground up, which included restoring the Australian Energy Storage Database (AESDB), new visualization tools, revalidating and verifying all project entries in the database, and adding additional policy-related features to the site.

Safety considerations for BESS: Before, during and after commissioning
Susan Schoenung, Longitude 122 West

Safety is a significant factor in the use of battery energy storage, as the desirable high energy density has the disadvantage of high fire risk. While the commissioning process is intended to check for both satisfactory system performance and safety features, other considerations both before and after commissioning can help ensure long life and safety of the system. Such considerations include battery selection and system design features, such as thermal barriers and circuit breakers. Important operations controlled by the battery management system include appropriate charge and discharge rates. Routine monitoring and control of temperatures and gases should be installed.

Battery State of Health Model

Vish Viswanathan, Pacific Northwest National Laboratory
Alasdair Crawford, Pacific Northwest National Laboratory

A coupled electrochemical/thermal model has been developed for multiple Li-ion battery chemistries. Thermal effects include reversible heat loss/gain from entropy change and irreversible losses associated with polarization losses. The model estimates performance and performance degradation for various operating conditions. Degradation from the loss of lithium and loss of active material have been estimated by considering parallel paths for solid electrolyte interphase formation. This model, along with a top-down model, has been validated against data presented in the literature.

Microgrid Evaluation Tool

Di Wu, Pacific Northwest National Laboratory

Designing and operating a microgrid with various distributed energy resources (DERs) including renewable generation and energy storage have received increasing attention during the past few years. In this work, we develop a methodology and tool to determine optimal sizes of various DERs considering both economic benefits and resilience performance of a microgrid. We model the interdependency between DER capacity and operation, and thereby simultaneously determine their optimal sizes and dispatch. To better capture the operation of DERs and their impacts on economic benefits and system resilience under diversified conditions, we model hourly microgrid operation over representative years and consider a population of stochastic grid disturbances. With the piecewise linearization technique, the optimal sizing problem is formulated using mixed-integer linear programming that can be efficiently solved even with a large number of system operating conditions.

State Regulatory Commission Energy Storage Outreach and Education

Howard Passell, Sandia National Laboratories

Energy storage technologies (ES) and their importance in the grid are advancing faster than policy makers and regulators can keep up, and ES economics and valuation are complex and challenging. Reaching out to states' regulatory commissions and offering them educational workshops on topics associated with ES is an important way to increase and enhance ES adoption across the country. In 2018-19 Sandia collaborated with PNNL on public utility commission (PUC) educational workshops in Hawaii, California, and the U.S. Southeast (in which 8 state PUCs participated). Prospective workshops for 2019-20 include New Mexico, Nevada, Iowa, New Jersey, and Texas.

Sandia National Laboratories Demonstration Summary

Daniel Borneo, Sandia National Laboratories
Benjamin Schenkman, Sandia National Laboratories

Energy storage is a key to enabling modernization of the electricity grid, including the successful integration of renewable and distributed energy resources. The DOE OE Energy Storage Program uses it Demonstrations Team at Sandia National Laboratories to address multiple challenges to the widespread deployment of energy storage: cost, creation of an equitable regulatory environment, safety and reliability, and industry acceptance. The team supports development, deployment, and research across multiple storage technologies and applications from transmission constrained regions in Alaska to hurricane-prone Puerto Rico, and from the off-grid rural corners of the Navajo Nation to the leading edge of emerging educational programs.

Materials I

Development of Zinc-Based Anodes for Aqueous MnO2/ Zn based Batteries

Matthew Fayette, Pacific Northwest National Laboratory

Zinc Anodes hold much promise for the next generation of batteries, owing to high theoretical capacity (820 mAh/g), availability, and stability in aqueous systems. However, it has been found that pure zinc anodes suffer from dendrite formation during charge cycles and overall cycle life. To this end, the proposed research aims to develop a zinc-rich zinc-copper alloy anode by electrodeposition of the alloy directly onto the current collector. The anode will then be subsequently assessed for cycling performance, where during the first discharge, the zinc will dissolve leaving a porous copper framework. Upon charging, the zinc in solution should deposit into the pores, mitigating dendrite formation on the surface, thereby stabilizing the anode.

Real-Time Identification and Understanding of Zinc Compounds in Rechargeable Zinc Electrodes

Brendan Hawkins, City College of New York

The discharge product in zinc metal electrodes has been studied for decades and is known to increase cell resistance and eventually result in passivation of the electrode. However, dynamic effects of voltage on the properties of the discharge product have seldom been investigated. In this work, we use in operando Raman spectroscopy and solid-state magic angle spinning NMR to investigate the effects of electrode potential on the composition and properties of the discharge product in zinc electrodes in alkaline media.

Rechargeable Zinc Manganese Dioxide Batteries: From Concept to Product

Jinchao Huang, Urban Electric Power

Traditional alkaline zinc manganese dioxide (Zn/MnO2) battery has a high energy storage capability per unit cost of materials but is limited in rechargeability. Urban Electric Power Inc. (UEP), in collaboration with the City University of New York (CUNY), has developed rechargeable Zn/MnO2 cells, which are made from the same environmentally benign, inexpensive and earth-abundant materials as the widely used primary alkaline cells, but can stably provide hundreds of cycles with a high energy density. In this presentation, technologies of Zn/MnO2 cells cycling in the 1st electron region ('one-electron' cell with 308 mAh/g-MnO2 theoretical capacity) and 2nd electron region ('two-electron' cell with 617 mAh/g-MnO2) of MnO2 will both be introduced. Challenges and technical breakthroughs needed for developing and manufacturing the rechargeable Zn/MnO2 batteries will be discussed.

Effects of Water-Soluble Binders on Electrochemical Performance of Manganese Dioxide Cathode in Mild Aqueous Zinc Batteries

Hee Jung Chang, Pacific Northwest National Laboratory

Binders are an important component for battery electrodes whose major function is to act as an effective dispersion agent. Additionally, binders connect the electrode species together and then steadily adhere them to the current collectors. In majority of rechargeable batteries including lithium ion batteries (LIBs), PVDF binders are the most commonly used binder for both the anode and cathode. However, using PVDF requires the organic solvent of N-methyl-2-pyrrolidone (NMP) which is expensive, volatile, combustible, toxic, low flexibility, and poor recyclability. Therefore, the goal of this program is to enhance the electrochemical performance of Zn/MnO2 aqueous batteries by using cost-effective and environmentally friendly binders. Our study demonstrates that observed water-soluble binders can be stable and offer desirable adhesion at certain pH levels (3.5-5) without any decomposition for long-cycle life.

Electrochemically Produced Zinc Oxide Electrode in Rechargeable Alkaline Batteries

Snehal Kolhekar, City College of New York

The zinc electrode is a commonly used negative electrode in a host of commercially important battery systems such as Zinc- Manganese dioxide (Zn-MnO2) and Silver – Zinc (Ag2O-Zn) batteries. However it's use in alkaline environment is greatly limited mainly due to its tendency for redistribution over the electrode surface and dendrite shorting. We demonstrate, here, a new cycling protocol that converts metallic zinc electrode into a highly oxidized and porous structure where the zinc particles are embedded within the porous ZnO matrix. Adopting this strategy resulted in double the cycle life at 12% utilization of the of the zinc electrode compared to a conventionally cycled metallic zinc electrode. Post-mortem analysis showed no membrane clogging along with substantially reduced zinc dendrites. A detailed quantitative shape change analysis as a function of cycle life revealed higher retention of active material on the electrode surface which is considered the reason for improved performance.

Theoretical Studies of the Electrochemical Properties of Bi- and Cu-Modified d-MnO2 Electrodes in Rechargeable Zn/MnO2 Batteries
Birendra Ale Magar, New Mexico State University

Alkaline Zn/MnO2 batteries hold great promise for electrical energy storage and load-leveling power grid applications due to their high energy density, non-toxicity, and low cost. Despite experimental evidence of the influence of Bi and Cu additives on the performance of rechargeable Zn/MnO2 batteries, the mechanism by which these additives affect the rechargeability and cyclability of the d-MnO2 electrode has not been explained in detail. We apply first-principles computational methods based on density functional theory to study the electrochemical properties of Bi- and Cu-modified delta-MnO2 electrodes in rechargeable Zn/MnO2 batteries. Our calculations show the possibility of formation of Bi-Mn and Cu-Mn oxides in Bi/Cu-modified d-MnO2 cathodes during battery cycling. The results of our study suggest that the formation of intermediate Bi-Mn and Cu-Mn oxides could reduce the rate of accumulation of irreversible redox reaction products in the MnO2 electrode.

Enabling Natural Graphite in High Voltage Aqueous Zinc-Graphite Dual Ion Batteries
Ismael Rodriguez Perez, Pacific Northwest National Laboratory

In this work, we present an aqueous Zinc DIB enabling natural graphite as a high voltage cathode and zinc as the anode using a Water-in-Salt electrolyte called the Zn-graphite dual-ion battery (ZnGDIB), where anions can be inserted into natural graphite at a record high voltage of 2.32 V in an aqueous solution. This year, the focus has been on elucidating the working mechanism of this relatively new concept to further optimize the system. The on-set potential for anion intercalation is ~1.4 V vs Ag/AgCl, and the ZnGDIB full cell voltage can reach 2.32 V or greater, making it the highest voltage in a Zn based configuration. The reversible capacity of the system is ~100 mAh/g with high rate capability reaching a capacity of nearly 50 mAh/g at 50C. A suite of characterization techniques have been employed to prove and gain insights into the anion intercalation mechanism into the natural graphite (NG). We have chosen NG as the candidate since synthetic graphite is very expensive to produce, deriving from petroleum coke and costing up to 10 times as much as the best natural graphite, therefore natural graphite would be the optimal choice considering large scale stationary energy storage.

Rechargeable Solid-State Copper Sulfide Cathodes for Alkaline Batteries: Importance of the Copper Valence State
Jonathan Duay, Sandia National Laboratories

Batteries for grid storage applications must be inexpensive, safe, reliable, as well as have a high energy density. Here, we utilize the high capacity of sulfur (S) (1675 mAh g-1, based on the idealized redox couple of S2-/S) in order to demonstrate for the first time, a reversible high capacity solid-state S-based cathode for alkaline batteries. It was found that in order for the S cathode to have the best cycle life in the solid-state it must not only be bound to Cu ions but bound to Cu ions in the +1 valence state, forming Cu2S as a discharge product. Zn/Cu2S batteries based on this chemistry provided a grid storage relevant energy density of > 42 W h L-1 (at 65 wt. % Cu2S loading), despite only using a 3% depth of discharge (DOD) for the Zn anode. This work opens the way to a new class of energy dense grid storage batteries based on high capacity solid-state S-based cathodes.

Safety Performance

Predicting and Mitigating Cascading Failure in Stacks of Lithium-Ion Cells
Andrew Kurzawski, Sandia National Laboratories

Whether or not a single point failure leads to a larger cascading failure depends on the system's ability to dissipate inadvertently released energy. We discuss predictive modeling of both inadvertent energy release and the dissipation of that energy. Predictive modeling also points out the limits of propagation offering the opportunity for sufficiently well validated models to define system designs that mitigate risks of localized failures. We use a series of Sandia cell-stack propagation measurements to assess the ability of predictive models to put bounds on predictive system analysis at the cell-stack level.

Internal Pressure Measurements during the Thermal Runaway of Cylindrical Lithium Ion Batteries

Frank Austin Mier, New Mexico Tech

Under abuse conditions, batteries exhibit a contained buildup of pressure during thermal runaway until the moment of vent mechanism burst. The ability to measure this pressure rise is important to understand the onset of venting and the preceding processes. Delicate components within cylindrical cells make directly accessing the inside of the battery impractical, so measurement of the cylindrical case's mechanical response to the pressure build up avoids this limitation. Here, experiments are performed to demonstrate how strain gauges may be used to perform noninvasive pressure measurement of batteries under thermal abuse conditions. A laboratory scale test apparatus has been constructed for these experiments, and analytical expressions have been established to describe internal pressure as a function of strain.

Thermal Runaway Testing and Database Development of Large-format Li-ion Cells at ORNL and SNL

June Stanley, Sandia National Laboratories

Large format Li-ion cells were extracted from Nissan Leaf and Chevy VOLT battery packs at ORNL. Single battery cells have been tested at SNL and ORNL as part of thermal runaway database development effort. A test protocol was developed for single-side indentation with specific test parameters, such as using a 6 mm diameter SS indenter, testing speed of 0.05 inch per minute – with test ending when a 100-mV voltage drop is seen, and six-point temperature monitoring. The batteries were charged to full capacity and then discharged to various state-of-charge (SOC). Nissan Leaf cells at 30%, 50%, 75% and 100% SOC were tested at SNL. Cells at 20%, 40%, 60%, 80% and 100% SOC were tested at ORNL. Test results on the Nissan Leaf batteries will be presented. The purpose of the study is to establish a multiple-parameter database on thermal runaway risks of Li-ion cells used in energy storage systems. The goal is to have a database with machine-learning capabilities which allows a user to perform a single indentation test on a partially charged Li-ion cell and obtain a thermal runaway risk score.

Mechanisms and Materials Impact of Abused Li-ion Batteries

Loraine Torres-Castro, Sandia National Laboratories

This work examines the application of Electrochemical Impedance Spectroscopy (EIS) and Differential Capacity calculations (dQ/dV) as tools for determining the state of stability (SOS) of an electrochemical cell or battery. The cells used for this study were commercial 10 Ah NMC pouch cells and 10Ah LFP cells subjected to electrical and thermal abuse coupled with EIS monitoring. This aims to not only provide a deeper understanding of how abused cells and batteries fail but also form the technical basis of a tool that could ultimately be used to interrogate cells of unknown stability and even monitor active cells for early signs of damage or failure. Fast impedance monitoring hardware previously developed at Idaho National Laboratory is used to provide not only monitoring after an abusive battery test but also look for changes in the cell while abusive conditions are applied. Differential capacity calculations are explored both before tests and after moderate levels of abuse to explore any noticeable changes that may be monitored during charge and discharge operations. The electrochemical techniques are supported with materials evaluations to further understand the impact of abusive conditions on the constituent materials.

Mitigation of Failure Propagation in Multi-Cell Lithium Ion Batteries

Loraine Torres-Castro, Sandia National Laboratories

Studies on the safety of lithium-ion batteries (LIBs) have long focused on the impact and aftermath of the field failure of a single cell. This has been driven by the fact that LIBs have traditionally been used for small devices where an isolated failure of a single cell would have little impact beyond the device and its user. Nevertheless, propagation of single cell failures in multi-cell batteries is a significant concern as batteries increase in scale for a variety of civilian and military applications. The work presented here examines the failure propagation behavior of small battery modules\ multi-module packs and the inclusion of a passive thermal management to investigate its effectiveness on the extent of propagation.

Partnerships

Energy Storage in the Future Puerto Rico Electric Grid
Frank Currie, Sandia National Laboratories

SNL is participating in a multi-lab effort to guide efforts to rebuild the Puerto Rico electric grid to be more resilient. The Energy Storage group is examining two key areas: the role of energy storage in the context of island-wide long term renewable energy goals and how energy storage can be used to increase resilience by allowing the grid to operate as multiple, independent minigrids following major disruptions such as those caused by Hurricane Maria in 2018. Outputs from this effort include developing a methodology to bound energy storage requirements for increasing levels of renewable penetration. The analysis also examines using existing hydroelectric resources to create resilient minigrids in the rural mountain interior of the island to avoid scenarios such as that following Maria when residents and businesses went many months without power.

Rural Electricity Resilience on the Navajo Nation
Frank Currie, Sandia National Laboratories

The 27,000 square mile territory of the Navajo Nation is served by the Navajo Tribal Utility Authority (NTUA). Established January 22, 1959, NTUA provides utility services for the region, including maintenance and expansion of electricity, communications, natural gas, water, and wastewater. One of the region's most abundant resources is solar irradiance, and NTUA deploys solar panels and traditional lead-acid batteries to provide electricity to Navajo people living in areas too remote to serve with power lines. Sandia is currently engaged in an effort to improve resiliency and reduce costs of residential energy storage systems by replacing existing lead acid batteries with Zinc Manganese-oxide batteries that have the potential to bring energy storage costs down to $50/kWh. SNL will monitor the three residential installations for one year to provide the information necessary to improve system performance and reliability.

Energy Resilience for the Seminole Tribe
Frank Currie, Sandia National Laboratories

The Seminole Tribe of Florida comprises six reservations with about 4100 members. Their electric power is provided by a system that experiences over 100 outages a year, so the Tribe is exploring the possibility of installing solar panels and energy storage to improve reliability and resilience. SNL is helping the Tribe to develop evaluation criteria for proposals to install solar and energy storage.

Update on the Natural Energy Laboratory of Hawaii Authority ESS and Microgrid Projects
Laurence Sombardier, Natural Energy Laboratory of Hawaii Authority (NELHA)

In the past year, NELHA's initiatives regarding energy storage and microgrid applications include studies and field demonstrations at NELHA's 900-acre tech park. The initiatives include studies such as a Hawaii Natural Energy Institute effort started this month to develop a plan to make NELHA carbon neutral and an ongoing Sandia energy storage study to investigate possible savings in the research campus. A 170kW PV array has been installed as well as a grid scale vanadium flow ESS. NELHA has leveraged existing partnerships and engaged with additional partners including three new Korean partners to develop a microgrid to operate its largest sea water pump station.

Energy Storage Valuation at San Carlos Apache Tribe
Rodrigo Trevizan, Sandia National Laboratories

San Carlos Apache Tribe is located in a sparsely populated region that has limited power generation and transmission resources next to Coolidge, Arizona. Currently, the energy tariffs are high and the system suffers from frequent power interruptions. To reduce costs and improve power quality, the tribe is currently installing solar photovoltaic arrays in several sites inside of the reservation. Sandia is currently performing studies to determine how energy storage systems associated with solar power generation can contribute to reduce the tribe's costs with electricity. The team has identified two sites for deployment of battery energy storage systems and the respective sizes of the systems.

ES Policy / Regulatory / Economic Workshop

Raymond Byrne, Sandia National Laboratories
Patrick Balducci, Sandia National Laboratories
Howard Passell, Sandia National Laboratories
Will McNamara, Sandia National Laboratories
Jeremy Twitchell, Pacific Northwest National Laboratory
Dhruv Bhatnagar, Pacific Northwest National Laboratory
Bobby Jeffers, Sandia National Laboratories

Sandia is actively engaged in multiple outreach efforts with other national labs and institutions across the U.S. aimed at advancing the understanding and implementation of energy storage (ES) systems for residential and grid scale use. In 2018 Sandia collaborated with PNNL in Hawaii on a day-long ES Introductory Workshop with the Hawaii PUC. Also in 2018, Sandia collaborated with NAATBatt and the City University of New York on the first Zinc Battery Technology Workshop, and is collaborating again with the same partners on the second zinc workshop planned for November, 2019. In 2019 Sandia has worked with PNNL on a day-long ES workshop with the California Energy Commission, and with PNNL and Southern Research on the two-day Southeast ES Symposium and PUC Workshop, in Birmingham Alabama, that hosted around 100 participants from the region, including PUC commissioners and staff from eight southeastern states. Future outreach efforts in 2019 and 2020 include PUC workshops in New Mexico, Nevada, New Jersey, Texas, Iowa, and Minnesota. Topics across all these events span ES technologies, testing, performance, commissioning, interconnection, valuation, safety, finance, and policy. In addition, Sandia is working with PNNL to identify ways to overcome obstacles in battery-to-grid interconnection policy, and with Urban Electric Power to develop a roadmap showing the path to a Zn-MnO2 battery with a consumer cost of less than $50/kWh.

PEER REVIEWER BIOS

VENKAT BANUNARAYANAN

Venkat Banunarayanan is the Senior Director of Integrated Grid at Business & Technology Strategies at the National Rural Electric Cooperatives Association. He has twenty-one years' experience in leading and executing energy-related projects involving power system analysis, data analytics, grid optimization, renewables integration, techno-economic feasibility and benefit-cost studies. At NRECA, his role is to lead the development of tools, resources and partnerships for member cooperatives to successfully evaluate opportunities for distribution grid optimization and value extraction, enabling reliable and cost-effective grid operations with high penetration of distributed energy, and business models for cooperatives to function as the trusted energy advisor for their communities. Venkat holds a doctorate in Electrical Engineering and an M.B.A in Finance, is certified as a Project Management Professional (PMP®), and has worked previously at the United States Department of Energy, ICF International, and General Electric in their Energy division.

STEPHEN BAYNE

Dr. Stephen B. Bayne received his Ph.D., MS and BS degrees in Electrical Engineering from Texas Tech University. After completing his doctoral studies, he joined the Naval Research Lab (NRL) where he was an electronics engineer designing advanced power electronics systems for space power applications. After two and a half years at NRL, Dr. Bayne transferred to the Army Research Lab (ARL) where he was instrumental in developing a high-temperature power electronic program. Dr. Bayne was promoted to Team Lead at ARL where he led the power components team which consisted of five engineers. As the Team Leader, Dr. Bayne was responsible for advanced research in high temperature and advance power devices for Army applications. After one and a half years as Team Lead, Dr. Bayne was promoted to Branch Chief of the Directed Energy Branch where he manages 16 Engineers, technicians and support staff. Dr. Bayne managed a multi-million dollar budget and was responsible for recruiting, development, and performance evaluation of members in the branch. After 8 years at the ARL, Dr. Bayne transitioned over to academia where he is a Full Professor at Texas Tech University. His research interests at Texas Tech are Power Electronics, Pulsed Power, Power Semiconductor and Renewable Energy.

FLORA FLYGT

Flora Flygt was in the electric utility industry for approximately 35 years in a variety of planning and leadership positions. She has worked for Madison Gas & Electric Company, Alliant Energy, and American Transmission Company LLC (ATC). She was involved in many innovative electric planning approaches including leading the development of integrated resource planning and participating in demand-side planning at Madison Gas & Electric Company. She implemented a leading-edge strategic flexibility approach to investment decisions at Alliant Energy, where she was Director of Corporate Research and Market Planning. As Director of Transmission Planning at ATC, Flora led the development of the first economically justified transmission project in MISO and of ATC's first Multi-Value Projects approved by MISO in 2011. She has been an expert witness on transmission planning, long-term electric forecasting, demand-side planning, and integrated resource planning. She has presented at and chaired many industry conferences and was very actively involved in the Eastern Interconnection Planning Collaborative. Flora holds an M.S. degree in Land Resources with a Master's certificate in Energy Analysis & Policy from the University of Wisconsin-Madison and a B.A. degree in Economics from the University of Michigan-Ann Arbor. Currently, Flora is an industry representative on the U.S. Department of Energy's Electricity Advisory Committee.

MARK GAISER

Mark Gaiser is an electrical engineer by training with a BSEE and MBA degree. He has worked over 20 years in the aerospace industry with experience in spacecraft power systems. Mark is presently working for the New Mexico State Energy Office promoting solar and wind energy sources, and is a member of the NM Solar Energy Association and the American Solar Energy Society.

JIM GREENBERGER

Jim Greenberger is the Executive Director of the National Alliance for Advanced Technology Batteries (NAATBatt), a not-for-profit trade association of companies involved in the manufacture of large format advanced batteries for automotive and grid-connected energy storage applications. Mr. Greenberger co-founded the predecessor of NAATBatt in 2008.

Prior to leading NAATBatt, Mr. Greenberger practiced law for more than 25 years, most recently as a partner at Reed Smith LLP in Chicago, where he led its cleantech practice group. Mr. Greenberger's law practice focused on mergers and acquisitions, private equity and venture capital transactions. He has represented some of the leading private equity and venture capital firms in the country and published several articles on private equity transactions and structures. He also writes a weekly column entitled "Executive Director's Notes" in the NAATBatt Advanced Battery Weekly.

In addition to his duties at NAATBatt, Mr. Greenberger serves on the Board of Directors of the Association for Corporate Growth-Chicago, on the governing board of the Kentucky-Argonne Battery Manufacturing Center, and is the principal of Private Equity Law Advisors, a private law practice in Chicago. He is a past chair of the Commercial Finance & Transactions Committee of the Chicago Bar Association and a member of the American Bar Association. He is a graduate of Haverford College and the University of Michigan Law School.

JONATHAN HAWKINS

Jonathan Hawkins is the Manager of Advanced Technology and Strategy at PNM Resources, an energy holding company based in Albuquerque New Mexico. Jonathan's team is responsible for providing research and development of new technologies and the proposal of possible business applications of emerging technologies in support of PNM Resources strategic objectives. Areas of responsibility include "smart grid" technologies and strategy, integration of distributed energy resources; plug in hybrid electric vehicles, and storage technologies. Jonathan Hawkins received his Bachelor of Science degree in Electrical Engineering from the University of New Mexico in 1994. After graduation, he went to work for Sumitomo Sitix Silicon, Inc. as an engineer responsible for semiconductor pre and post production material characterization. Jonathan joined PNM Resources in 2002 where he managed PNM's Distribution Standards organization, which provides material specifications and model standards for design and construction of utility infrastructure. In 2010 he became the Manager of the Advanced Technology group. Jonathan is a member of the Institute of Electrical and Electronics Engineers (IEEE), a member of the Research Advisory Committee to EPRI as well as an advisor to multiple individual research programs, and an invited reviewer for proposals to the Department of Energy.

PEER REVIEWER BIOS

C. MICHAEL HOFF

Michael Hoff has over 30 years of experience in electric utilities, uninterruptible power supplies, advanced energy storage, battery systems, communications, manufacturing and construction. He is currently CTO and VP of Research and Technology and directs the research and modeling of advanced energy storage technologies at NEC.

Mr. Hoff was the first member of A123's Energy Solutions Group, where he helped build the core systems engineering capability for the company before it was acquired by NEC. Before that, Mr. Hoff served 18 years in various roles developing UPS products for American Power Conversion. This experience gave him broad exposure in energy storage technologies, power control, electronic controls and communications, manufacturing processes and the power market. Michael holds a BS in Electrical Engineering and Power from Drexel University, and a MS in Electrical Engineering and Power from Northeastern University.

PRAMOD KULKARNI

Pramod joined the Customized team in January 2013. He is a Senior Consultant in the Emerging Technologies Group that focuses on regulatory, technology, and market developments that create opportunities for clients in emerging technologies sector, including energy storage. Pramod brings 30+ years of experience. Prior to joining Customized, Pramod worked at the California Energy Commission for 23 years where he managed programs that provided funding for development and demonstration of renewable energy, energy storage, demand response and industrial energy efficiency. Before joining the Energy Commission, Pramod worked in the private sector that included working for a Fortune 100 company as a financial analyst, with an energy consulting company, an angel investor and a startup. Pramod has a BS and MS from India and an MBA from the US.

BOR YANN LIAW

Bor Yann Liaw is the Manager of the Energy Storage and Advanced Vehicles Department at Idaho National Laboratory (INL). There, he oversees an R&D program on batteries and advanced vehicle evaluations. Prior to INL, Liaw held a position at the Hawaii Natural Energy Institute, where he focused on advanced power source systems for vehicle and energy storage applications.

Liaw has been in the field of electric and hybrid vehicle evaluation and advanced battery diagnostics and prognostics for the past three decades. His major research activities comprise laboratory and real-life battery and vehicle testing, data collection and analysis, battery modeling and simulation, battery performance and life prediction, battery rapid charging technology development, and battery diagnoses and prognoses.

Over the past two decades, Liaw has been involved in many professional organizations, including: ECS, International Society of Solid State Ionics, and the International Battery Association. He has co-authored more than 150 technical papers, seven book chapters, and eight patents and patent applications. He is currently the Associate Editor for the Journal of The Electrochemical Society.

MADHAV MANJREKAR

Dr. Madhav Manjrekar, Senior Member of IEEE, is an Associate Professor at the University of North Carolina in Charlotte and also serves as an Assistant Director of the Energy Production & Infrastructure Center (EPIC). Named as an e4 Carolinas Emerging Leader in Energy in 2015, Dr. Manjrekar has led technology and innovation teams in the areas of energy and power systems for more than 15 years. Prior to joining academia in 2012, he worked as the Vice President of Global Research and Innovation at Vestas (the wind turbine company), and previously has held various leadership and management positions at Siemens, Eaton and ABB. Dr. Manjrekar holds 10 US and international patents, has published over 55 journal and conference papers and has received multiple IEEE prize paper awards. He has also served on various task forces, including High Mega-Watt Leadership Team of National Institute of Standards and Technology, the Smart Grid Task Force of North American Electric Reliability Corporation, IEEE Standard P2030, and on review panels for ARPA-E, and the National Science Foundation. Dr. Manjrekar's research interests are in applications of power electronics in utility power systems and variable speed motor drives, interfaces for renewable power generation and energy storage, smart grids, and cyber vulnerability of electric infrastructure. Dr. Madhav Manjrekar received his B.E. degree from Government College of Engineering, Pune, India, his M.Tech. from Indian Institute of Science, Bangalore, India, M.S. from Montana State University, Bozeman, Montana, and Ph.D. from University of Wisconsin, Madison, Wisconsin, in 1993, 1995, 1997, and 1999 respectively.

STEVE MARTIN

Steve W. Martin received his Ph.D. in Physical Chemistry from Purdue University in 1986. He joined the Department of Materials Science & Engineering at Iowa State University and was promoted to Associate Professor in 1991, Full Professor in 1996, University Professor in 2006, and Anson Marston Distinguished Professor in Engineering in 2009. He has won the George W. Morey Award in Glass Science from the Glass and Optical Materials Division of the American Ceramic Society, where he is a named Fellow. His research specialization is the study of glass, and ionically conducting glassy solid electrolytes for batteries and fuel cells. He has published more than 200 refereed articles, given more than 250 invited talks around the world.

DR. MICHAEL MAZZOLA

Dr. Michael Mazzola is the Director of the Energy Production and Infrastructure Center (EPIC) and the Duke Energy Distinguished Chair in Power Engineering Systems at UNC Charlotte.

Dr. Mazzola holds a Ph.D. in electrical engineering from Old Dominion University. After three years in government service at the Naval Surface Warfare Center in Dahlgren, Virginia, in 1993 he joined the faculty at Mississippi State University where he became known for his research in the areas of silicon carbide power semiconductor device prototyping and semiconductor materials growth and characterization. For the past 10 years he served at the Mississippi State University Center for Advanced Vehicular Systems as the associate director for advanced vehicle systems, where he leads research in high-voltage engineering, power systems modeling and simulation, the application of silicon carbide semiconductor devices in power electronics, and the control of hybrid electric vehicle power trains. In addition, he served two years as the chief technology officer of SemiSouth Laboratories, a company he co-founded.

PEER REVIEWER BIOS

NEVILLE MOODY

Neville Moody obtained his PhD degree in Materials Science from the University of Minnesota in1981. After joining Sandia National Laboratories, his research focused on the determination of hydrogen effects on deformation and fracture in titanium, stainless steels, and superalloys, employing experimental testing, modeling, and simulation techniques. For the past 20 years his research has included the study of deformation and fracture on the submicron scale in thin films and small volumes. He has given more than 100 invited presentations and authored or co-authored more than 170 publications, including invited reviews and chapters in the encyclopedia on Comprehensive Structural Integrity and the encyclopedia of Gaseous Hydrogen Embrittlement of High Performance Metals in Energy Systems. Dr. Moody has co-organized three International Conferences on Hydrogen Effects in Materials, three International Conferences on Environmental Damage in Structural Materials, three regional materials and welding technology conferences, and 23 symposia for materials societies and topical conferences. He co-chaired the 2005 MRS Spring Meeting in San Francisco and was vice chair 2012 and chair 2014 of the Gordon Conferences on Thin Film and Small Volume Mechanical Behavior. He served as the Director of Programming on the TMS Board of Directors from 2012 until 2015. He also managed the Sandia National Laboratories Energy Nanomechanics Department from 2011 until 2015. Dr. Moody is an active member of several TMS and MRS committees and is a Fellow of ASM International and MRS.

MICHAEL PERRY

Michael Perry is the associate director of United Technologies Research Center since September 2008. He is an experienced Technology and Project Leader with a proven history of working in the Clean Energy R&D industry. He has been the Principal Investigator of four ARPA-E projects in the past 10 years, with expertise in Fuel Cells, Flow Batteries, Flow Cell Diagnostics, and Mass Transport & Durability of Electrochemical Systems. Michael is the sole or co-inventor on more than 60 issued U.S. Patents, to date.

DR. VITTAL S. RAO

Dr. Vittal S. Rao is a professor and Electrical and Computer Engineering and Director at Smart Grid Energy Center (SGEC) at Texas Tech University. His research interests include Cyber Security of SCADA Control Systems, Smart Grid and Microgrid Systems, Smart Structural Systems, Control of Wind Turbines; Cyber Security of Smart Grid Systems; Robust Control Systems. He has supervised 198 publications, developed three multidisciplinary courses in smart structures and structural health monitoring, and developed a state-of-the-art research laboratory in Smart Grid using the Major Research grant of NSF. Dr. Rao received his Ph.D. at the Indian Institute of Technology in New Delhi.

UZMA SIDDIQI

Uzma Siddiqi is the Automation Engineering Supervisor at Seattle City Light, the electric utility serving Seattle and environs. Uzma initiated Seattle City Light's 100% clean microgrid at the city's Miller Community Center. Previously, she has worked in Technology Innovation, Transmission and Distribution Planning, Engineering Standards, and Customer Service. She has been in the electric power industry for many years and spent some years as a stay-at-home mom. Uzma received her BS and MS degrees in Electrical Engineering from North Carolina State University. She is currently working on a second Masters degree for fun and the learning, of course.

RAMTEEN SIOSHANSI

Ramteen Sioshansi is a professor in and the associate chair of the Department of Integrated Systems Engineering and an associate fellow in the Center for Automotive Research at The Ohio State University. He holds a B.A. in economics and applied mathematics and an M.S. and Ph.D. in industrial engineering and operations research from the University of California, Berkeley and an M.Sc. in econometrics and mathematical economics from the London School of Economics and Political Science. Prior to joining OSU, he was a postdoctoral research fellow at the National Renewable Energy Laboratory.

His research focuses on the integration of advanced energy technologies, including renewables, energy storage, and electric transportation, into energy systems. He also works in energy policy and electricity market design, especially as they pertain to advanced energy technologies.

He has published numerous academic journal articles and serves on the editorial boards of the Foundations and Trends in Energy Markets and Policy, IEEE Transactions on Power Systems, Journal of Energy Engineering, IET Renewable Power Generation, and Journal of Modern Power Systems and Clean Energy. He received the 2010 Campbell Watkins Energy Journal Best Paper Award from the International Association for Energy Economics. He is currently serving a third term on the Electricity Advisory Committee of the U.S. Department of Energy and is chair of its Energy Storage Subcommittee. In addition to his academic research and teaching, Professor Sioshansi has been a consultant to numerous public and private organizations.

GRIGORII SOLOVEICHIK

Dr. Grigorii Soloveichik currently serves as a Program Director at the Advanced Research Projects Agency-Energy (ARPA-E). His focus at ARPA-E includes developing electrochemical devices, advanced materials and processes for energy electrochemical and chemical storage and conversion. He created and manages REFUEL program targeting the production of carbon neutral fuels from renewable sources and their use for energy storage and transportation.

Prior to joining ARPA-E, Soloveichik worked as a GE Global Research as a Senior Staff Chemist, in addition to being the Director of the DOE funded Energy Frontier Research Center for Electrocatalysis, Transport Phenomena, and Materials for Innovative Energy Storage. While there, he developed novel rechargeable liquid fuel cells and high energy density flow batteries, designed catalytic and electrochemical processes for functionalization of arenes and phenols, and developed novel electrolytes and electrocatalysts. His previous work included development of catalysts and lithium-sulfur rechargeable batteries. He is the author/coauthor of 71 issued US patents and 125+ papers in peer-reviewed journals.

He holds the degrees of M.S. in Chemistry, Ph.D. in Inorganic Chemistry, and D.Sc. in Chemistry from Moscow State University.

DR. TONY VAN BUUREN

Dr. Tony Van Buuren is currently working as a Professor in the Department of Materials Science Division, Lawrence Livermore National Laboratory, United States. His research interests includes Materials Science. He is serving as an editorial member and reviewer of several international reputed journals. Dr. Tony Van Buuren is the member of many international affiliations, and has authored many research articles and books related to Materials Science.

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