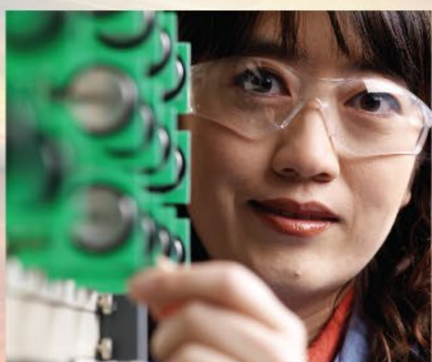


Pacific Northwest NATIONAL LABORATORY

Proudly Operated by Battelle Since 1965

DOE OE Stationary Energy Storage Program at PNNL

Vincent Sprenkle
Pacific Northwest National Laboratory

Support from DOE Office of Electricity Energy Storage Program

OE Energy Storage Peer Program Review
Santa Fe, NM
September 25th-27th, 2018

DISCOVERY *in Action*

U.S. DEPARTMENT OF ENERGY

DOE OE Storage Program Structure at PNNL

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle *Since 1965*

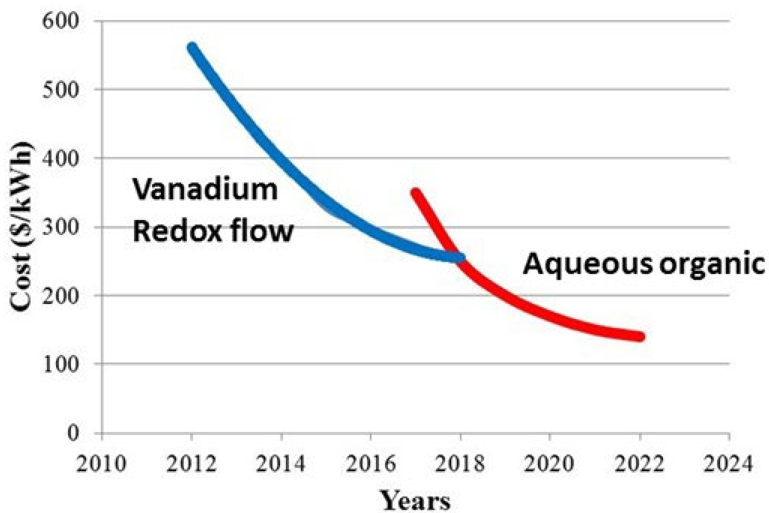
- **Cost Competitive Technologies (Wei Wang)**
  - *Develop material and system enhancements to resolve key cost and performance challenges for energy storage devices.*
- **Safety and Reliability (David Reed)**
  - *Develop scientifically derived knowledge base for new protocols and standards to enable safer and more energy storage systems.*
- **Equitable Regulatory Environment (Rebecca O'Neil/Jeremy Twitchell)**
  - *Support an equitable regulatory environment for energy storage applications by providing information and analysis with regulators to support advanced investigations into storage.*
- ***Industrial Acceptance (Patrick Balducci)***
  - *Enable the confident development, deployment and operation of grid energy storage through controlled testing and valuation of field deployed systems.*

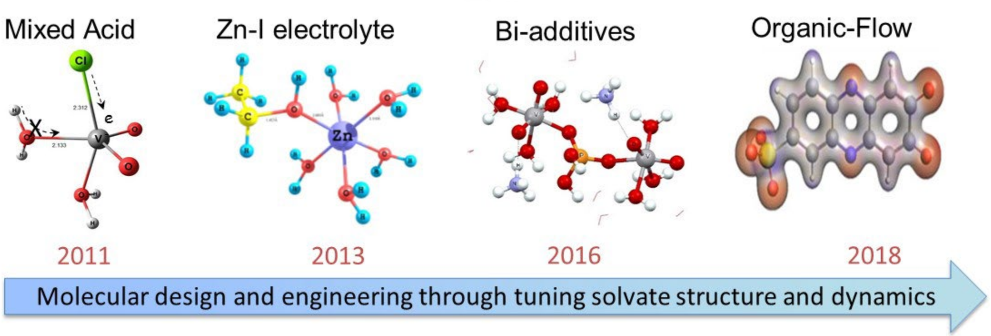
Cost Competitive Technologies

Flow Battery Development

Pacific Northwest
NATIONAL LABORATORY
Proudly Operated by **Battelle** *Since 1965*

FY18: *Demonstrated new Aqueous Soluble Organic (ASO) redox flow battery electrolyte capable of meeting $250/kWh cost target for a projected1MW/4MWh system*



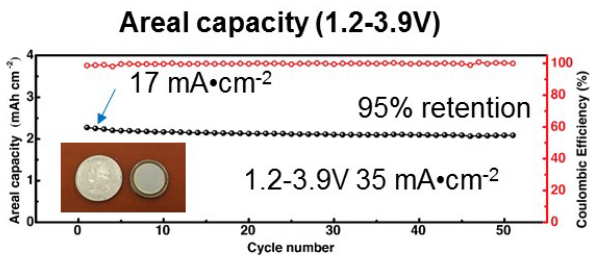


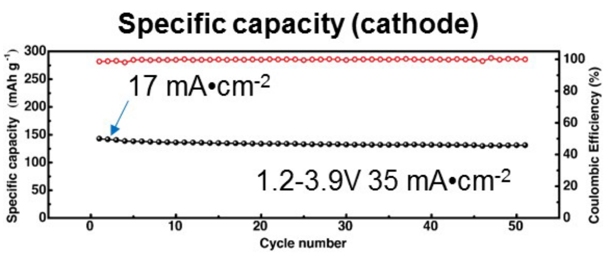
- Wei Wang – PNNL Session Thrust (9/25 - 4:00-5:15 pm)
- Vijay Murugesan - Flow Battery Electrolyte Chemistry Development (9/25 – 4:00 pm)
- Aaron Hollas - Aqueous Soluble Flow Battery Development (9/25 – 4:15 pm)
- Zimin Nie – Mechanistic Understanding of V Electrolytes (Poster: 9/26 – 5:00 pm)
- Michael Aziz (Harvard) – Alkaline ASO Flow Battery Electrolytes (9/26 – 2:30 pm)
- Brian Berland (ITN) -Advanced Bi-additive Vanadium Sulfate Electrolyte (9/26 – 3:45 pm)

Cost Competitive Technologies
Na based technologies

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

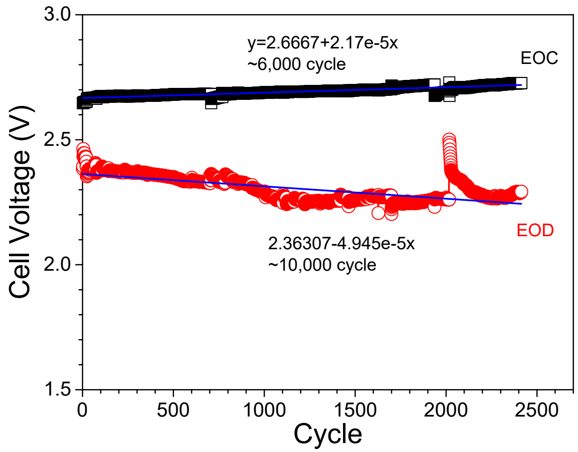
FY18: *Developed and demonstrated three novel sodium ion anode materials with capacities (350 mAh/g) comparable to Li-ion*
FY19 – scale to pouch cells





- Xiaolin Li - Na-ion Battery Development (9/25 - 4:45pm)
- Biwei Xiao – Cathode Materials for Na-ion Batteries (Poster: 9/26 – 5:00 pm)

FY18*: Demonstrated 40% improvement in energy density for low-cost N-$FeCl_2$ battery enabling complete usage of available material capacity.*

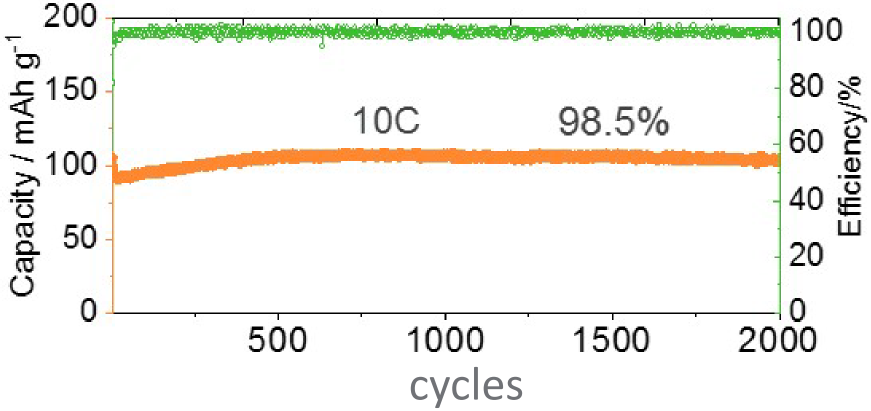


- Guosheng Li - Intermediate Temperature Na-metal Halide (9/25 - 4:30pm)
- Xiaochuan Lu – Fabrication of Flexible Composite Electrolytes (Poster: 9/26 – 5:00 pm)
- Guosheng Li – Cell Design and Testing of Na-Metal Halide (Poster: 9/26 – 5:00 pm)

Cost Competitive Technologies

Zn – MnO_2 batteries

F18: *Identified neutral pH electrolyte and electrode components to stabilize Zn-MnO_2 over thousands of cycles*



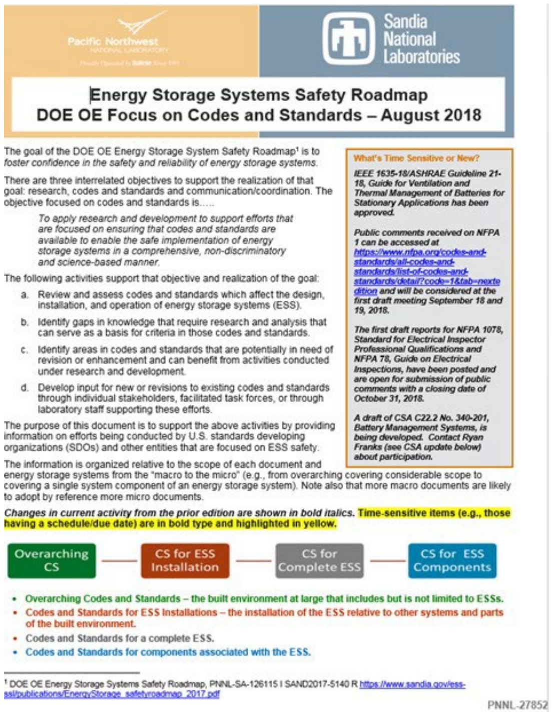
- Huilin Pan – Mild Aqueous Electrolytes for Zn-MnO_2 (Poster: 9/26 – 5:00 pm)
- Hee Jung Chang - Zn-MnO_2 Battery Characterization (Poster: 9/26 – 5:00 pm)

Safety and Reliability Thrust

Safety

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

FY18: *Initiated monthly Storage CSR newsletter.*



Pacific Northwest NATIONAL LABORATORY | Sandia National Laboratories

Energy Storage Systems Safety Roadmap
DOE OE Focus on Codes and Standards – August 2018

The goal of the DOE OE Energy Storage System Safety Roadmap[1] is to *foster confidence in the safety and reliability of energy storage systems.*

There are three interrelated objectives to support the realization of that goal: research, codes and standards and communication/coordination. The objective focused on codes and standards is…..

> *To apply research and development to support efforts that are focused on ensuring that codes and standards are available to enable the safe implementation of energy storage systems in a comprehensive, non-discriminatory and science-based manner.*

The following activities support that objective and realization of the goal:

a. Review and assess codes and standards which affect the design, installation, and operation of energy storage systems (ESS).
b. Identify gaps in knowledge that require research and analysis that can serve as a basis for criteria in those codes and standards.
c. Identify areas in codes and standards that are potentially in need of revision or enhancement and can benefit from activities conducted under research and development.
d. Develop input for new or revisions to existing codes and standards through individual stakeholders, facilitated task forces, or through laboratory staff supporting these efforts.

The purpose of this document is to support the above activities by providing information on efforts being conducted by U.S. standards developing organizations (SDOs) and other entities that are focused on ESS safety.

What's Time Sensitive or New?

IEEE 1635-18/ASHRAE Guideline 21-18, Guide for Ventilation and Thermal Management of Batteries for Stationary Applications has been approved.

Public comments received on NFPA 1 can be accessed at https://www.nfpa.org/codes-and-standards/all-codes-and-standards/list-of-codes-and-standards/detail?code=1&tab=nextedition and will be considered at the first draft meeting September 18 and 19, 2018.

The first draft reports for NFPA 1078, Standard for Electrical Inspector Professional Qualifications and NFPA 78, Guide on Electrical Inspections, have been posted and are open for submission of public comments with a closing date of October 31, 2018.

A draft of CSA C22.2 No. 340-201, Battery Management Systems, is being developed. Contact Ryan Franks (see CSA update below) about participation.

The information is organized relative to the scope of each document and energy storage systems from the "macro to the micro" (e.g., from overarching covering considerable scope to covering a single system component of an energy storage system). Note also that more macro documents are likely to adopt by reference more micro documents.

Changes in current activity from the prior edition are shown in bold italics. **Time-sensitive items (e.g., those having a schedule/due date) are in bold type and highlighted in yellow.**

Overarching CS — CS for ESS Installation — CS for Complete ESS — CS for ESS Components

- Overarching Codes and Standards – the built environment at large that includes but is not limited to ESSs.
- Codes and Standards for ESS Installations – the installation of the ESS relative to other systems and parts of the built environment.
- Codes and Standards for a complete ESS.
- Codes and Standards for components associated with the ESS.

[1] DOE OE Energy Storage Systems Safety Roadmap, PNNL-SA-126115 I SAND2017-5140 R https://www.sandia.gov/ess-ssl/publications/EnergyStorage_safetyroadmap_2017.pdf

PNNL-27852

Energy Storage Systems Roadmap

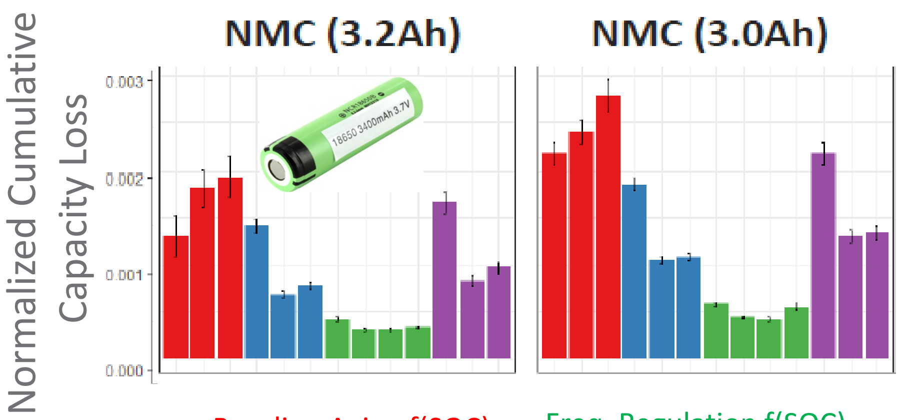
FY18: *Hosted 2018 Energy Storage Systems Safety and Reliability Forum in Seattle. 100 attendees*

- Charlie Vartanian - Codes and Standards Update (9/26 – 3:15 pm)
- Charlie Vartanian – IEEE ES Task Force Overview (9/26 – 5:00 pm)

Safety and Reliability
Reliability

Pacific Northwest
NATIONAL LABORATORY
Proudly Operated by **Battelle** *Since 1965*

FY18: *Continued testing on Li ion cells (NMC, NCA, LFP) showing impact of grid duty cycles*



Baseline Aging f(SOC)
Baseline EV f(SOC)
Freq. Regulation f(SOC)
Peak Shaving f(SOC)

ESS Systems Reliability Laboratory

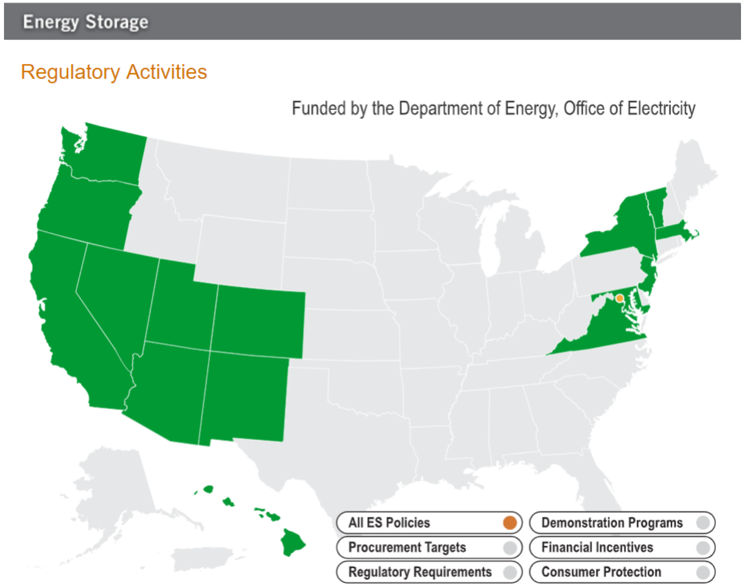
FY18: *Launched ESS Reliability Lab to provide Independent validation of kW scale; flow, Li-ion, Na-metal halide, Pb-acid systems under grid duty cycles.*

- Daiwon Choi - Li-ion Battery Chemistries under Grid Duty Cycles (9/25 – 5:00 pm
- David Reed – Reliability Laboratory at PNNL (Poster: 9/26 – 5:00 pm)
- Bin Li – Reliability studies V/V RFB batteries (Poster: 9/26 – 5:00 pm)

Regulatory and Industrial Acceptance

FY18: *Developed 1-day Energy Storage Seminar for (WECC) and the State PUC's within WECC.*

FY18*: Established MOU with Public Utility Commission of Nevada (PUCN) to provide technical support to the PUC as they implement Nevada State Bill 204*



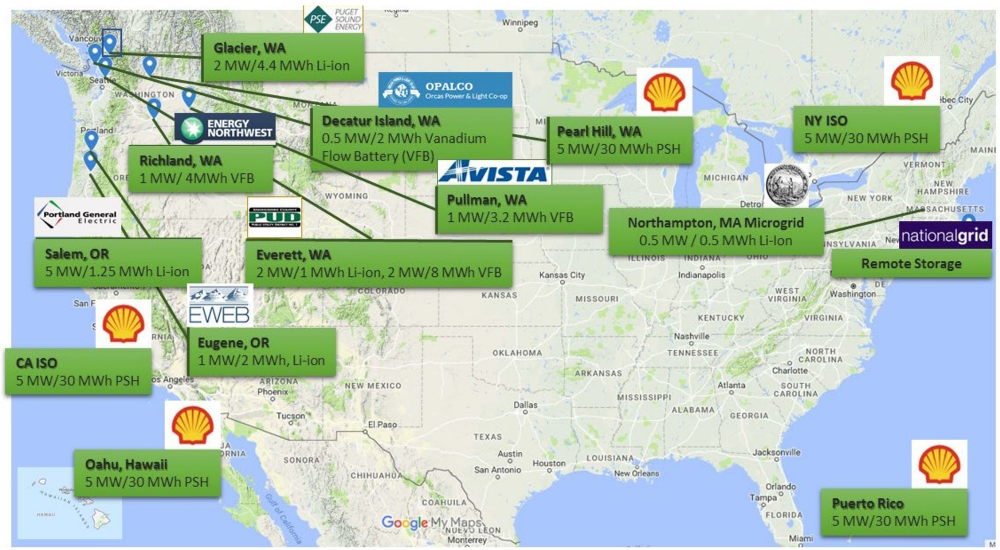
FY18: *Launched Energy Storage Policy Database*

- Jeremy Twitchell - State Regulatory Engagement (9/25 – 3:00 pm)
- Jeremy Twitchell – IRP Analysis (9/26 – 5:00 pm)

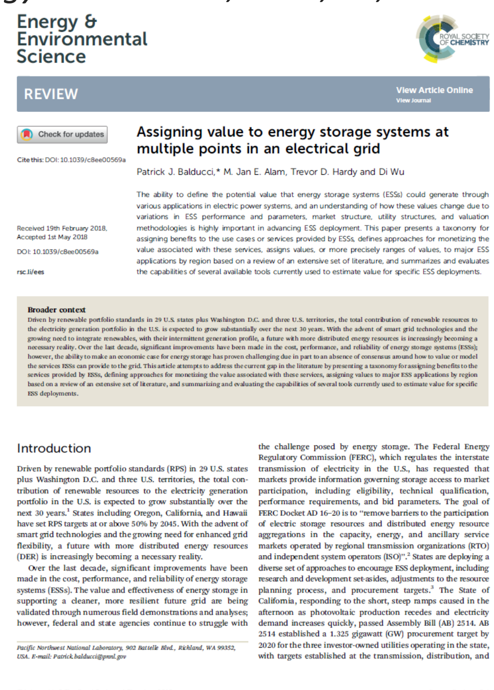
Industrial Acceptance

Supporting 100MWh at 13 sites

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle *Since 1965*



Energy Environ. Sci., 2018, 11, 1926—1944



Energy & Environmental Science

ROYAL SOCIETY OF CHEMISTRY

REVIEW

View Article Online
View Journal

Check for updates

Cite this: DOI: 10.1039/c8ee00569a

Assigning value to energy storage systems at multiple points in an electrical grid

Patrick J. Balducci,* M. Jan E. Alam, Trevor D. Hardy and Di Wu

Received 19th February 2018,
Accepted 1st May 2018

DOI: 10.1039/c8ee00569a

rsc.li/ees

The ability to define the potential value that energy storage systems (ESSs) could generate through various applications in electric power systems, and an understanding of how these values change due to variations in ESS performance and parameters, market structure, utility structures, and valuation methodologies is highly important in advancing ESS deployment. This paper presents a taxonomy for assigning benefits to the use cases or services provided by ESSs, defines approaches for monetizing the value associated with these services, assigns values, or more precisely ranges of values, to major ESS applications by region based on a review of an extensive set of literature, and summarizes and evaluates the capabilities of several available tools currently used to estimate value for specific ESS deployments.

Broader context

Driven by renewable portfolio standards in 29 U.S. states plus Washington D.C. and three U.S. territories, the total contribution of renewable resources to the electricity generation portfolio in the U.S. is expected to grow substantially over the next 30 years. With the advent of smart grid technologies and the growing need to integrate renewables, with their intermittent generation profile, a future with more distributed energy resources is increasingly becoming a necessary reality. Over the last decade, significant improvements have been made in the cost, performance, and reliability of energy storage systems (ESSs); however, the ability to make an economic case for energy storage has proven challenging due in part to an absence of consensus around how to value or model the services ESSs can provide to the grid. This article attempts to address the current gap in the literature by presenting a taxonomy for assigning benefits to the services provided by ESSs, defining approaches for monetizing the value associated with these services, assigning values to major ESS applications by region based on a review of an extensive set of literature, and summarizing and evaluating the capabilities of several tools currently used to estimate value for specific ESS deployments.

Introduction

Driven by renewable portfolio standards (RPS) in 29 U.S. states plus Washington D.C. and three U.S. territories, the total contribution of renewable resources to the electricity generation portfolio in the U.S. is expected to grow substantially over the next 30 years.[1] States including Oregon, California, and Hawaii have set RPS targets at or above 50% by 2045. With the advent of smart grid technologies and the growing need for enhanced grid flexibility, a future with more distributed energy resources (DER) is increasingly becoming a necessary reality.

Over the last decade, significant improvements have been made in the cost, performance, and reliability of energy storage systems (ESSs). The value and effectiveness of energy storage in supporting a cleaner, more resilient future grid are being validated through numerous field demonstrations and analyses; however, federal and state agencies continue to struggle with the challenge posed by energy storage. The Federal Energy Regulatory Commission (FERC), which regulates the interstate transmission of electricity in the U.S., has requested that markets provide information governing storage access to market participation, including eligibility, technical qualification, performance requirements, and bid parameters. The goal of FERC Docket AD 16–20 is to "remove barriers to the participation of electric storage resources and distributed energy resource aggregations in the capacity, energy, and ancillary service markets operated by regional transmission organizations (RTO) and independent system operators (ISO)".[2] States are deploying a diverse set of approaches to encourage ESS deployment, including research and development set-asides, adjustments to the resource planning process, and procurement targets.[3] The State of California, responding to the short, steep ramps caused in the afternoon as photovoltaic production recedes and electricity demand increases quickly, passed Assembly Bill (AB) 2514. AB 2514 established a 1.325 gigawatt (GW) procurement target by 2020 for the three investor-owned utilities operating in the state, with targets established at the transmission, distribution, and

Pacific Northwest National Laboratory, 902 Battelle Blvd., Richland, WA 99352, USA. E-mail: Patrick.balducci@pnnl.gov

- ***FY18***: *Supported economic benefits analysis of various storage technologies at 10 sites across the U.S.*
- ***FY18:*** *Developed Optimization Performance Evaluation Tool (OPET) software tool for analyzing the performance of energy storage controls systems*

> - *PNNL Industrial Acceptance Session overview (Patrick Balducci 9/25 – 2:00 pm*
> - Vish Viswanathan - Battery Storage State of Health Model (9/25 – 2:10 pm)
> - Jan Alam - Control System Enhancement Using the OPET (9/25 – 2:20 pm)
> - Di Wu - HECO Demand Response Tool (9/25 – 2:30 pm)
> - Kendall Mongrid – Market Analysis Small Modular Pumped Hydro (9/26 – 5:00 pm)
> - Alastair Crawford – WA CEF Performance Results (9/26 – 5:00 pm)

FY18 Publications

1. Biwei Xiao, Fernando Soto, Meng Gu, Kee Sung Han, Junhua Song, Hui Wang, Mark H. Engelhard, Vijayakumar Murugesan, Karl T. Mueller, David Reed, Vincent Sprenkle, Perla B. Balbuena, Xiaolin Li."Lithium-Pretreated Hard Carbon as High-Performance Sodium-Ion Battery Anodes."***Advanced Energy Materials*** 8 (24) 1801441 (August 2018).
2. Guosheng Li."Turning Cooler."***Nature Energy*** (August 2018).
3. Keeyoung Jung, Hee-Jung Chang, Jeffery F. Bonnett, Nathan L. Canfield, Vincent L. Sprenkle, Guosheng Li."An advanced Na-NiCl2 battery using bi-layer (dense/micro-porous) β″-alumina solid-state electrolytes."***Journal of Power Sources*** 396: 297-303 (August 2018).
4. Damien Saurel, Brahim Orayech, Biwei Xiao, Daniel Carriazo, Xiaolin Li, Teófilo Rojo."From Charge Storage Mechanism to Performance: A Roadmap toward High Specific Energy Sodium-Ion Batteries through Carbon Anode Optimization."**Advanced Energy Materials** 8 (17) 1703268 (June 2018).
5. Junhua Song, Biwei Xiao, Yuehe Lin, Kang Xu, Xiaolin Li."Interphases in Sodium-Ion Batteries."***Advanced Energy Materials*** 8 (17) 1703082 (June 2018).
6. Aaron Hollas, Xiaoliang Wei, Vijayakumar Murugesan, Zimin Nie, Bin Li, David Reed, Jun Liu, Vincent Sprenkle & Wei Wang."A biomimetic high-capacity phenazine-based anolyte for aqueous organic redox flow batteries."***Nature Energy*** 3: 508-514 (June 2018).
7. Patrick J. Balducci, M. Jan E. Alam, Trevor D. Hardy, Di Wu."Assigning value to energy storage systems at multiple points in an electrical grid."***Energy & Environmental Science*** (June 2018).
8. Xie C,Zhang H,Xu W, Wang W, Li X. "'A Long Cycle Life, Self-Healing Zinc-Iodine Flow Battery with High Power Density" ***Angew Chem*** Internatioan Ed. (May, 2018)
9. Zhaoxin Yu, Shun-Li Shang, Yue Gao, Daiwei Wang, Xiaolin Li, Ki-Kui Liu, Donghai Wang."A quaternary sodium superionic conductor - Na10.8Sn1.9PS11.8."***Nano Energy*** 47: 325-330 (May 2018).

FY18 Publications (cont.)

10. Daiwon Choi, Prashanth H. Jampani, J.R.P. Jayakody, Steven G. Greenbaum, Prashant N. Kumta."Synthesis, surface chemistry and pseudocapacitance mechanisms of VN nanocrystals derived by a simple two-step halide approach."***Materials Science and Engineering***: B 230: 8-19 (April 2018).
11. Alasdair J. Crawford, Qian Huang, Michael C.W. Kintner-Meyer, Ji-Guang Zhang, David M. Reed, Vincent L. Sprenkle, Vilayanur V. Viswanathan, Daiwon Choi."Lifecycle comparison of selected Li-ion battery chemistries under grid and electric vehicle duty cycle combinations."***Journal of Power Sources*** 380: 185-193 (March 2018).
12. Saurel, D; Orayech, B; Xiao, B; Carriazo, D; Li,X;Rojo T. "'From Charge Storage Mechanism to Performance: A Roadmap toward High Specific Energy Sodium-Ion Batteries through Carbon Anode Optimization" ***Advanced Energy Materials***. (March, 2018)
13. Chang HJ ,Lu X ,Bonnett J F,Canfield N L,Son S ,Park YC ,Jung K ,Sprenkle V L,Li G. "'Ni-less' Cathodes for High Energy Density, Intermediate Temperature"***Advanced Materials Interfaces***. 1701592 (March, 2018)
14. Shaofang Fu, Junhua Song, Chengzhou Zhu, Gui-Liang Xu, Khalil Amine, Chengjun Sun, Xiaolin Li, Mark H Engelhard, Dan Du, Yuehu Lin."Ultrafine and highly disordered Ni2Fe1 nanofoams enabled highly efficient oxygen evolution reaction in alkaline electrolyte."***Nano Energy*** 44: 319-326 (February 2018).
15. Pan, H.; Li, B.; Mei, D.; Nie, Z.; Shao, Y.; Li, G.; Li, X. S.; Han, K. S.; Mueller, K. T.; Sprenkle, V.; Liu, J. " Controlling Solid–Liquid Conversion Reactions for a Highly Reversible Aqueous Zinc–Iodine Battery" ACS Energy Letters 2:2674-2680 (Oct. 2017).
16. Junhua Song, Pengfei Yan, Langli Luo, Xingguo Qi, Xiaohui Rong, Jianming Zheng, Biwei Xiao, Shuo Feng, Chongmin Wang, Yong-Sheng Hu, Yuehe Lin, Vincent L. Sprenkle, Xiaolin Li."Yolk-shell structured Sb@C anodes for high energy Na-ion batteries."***Nano Energy*** 40: 504-511 (October 2017).
17. Lu, X, HJ Chang, JF Bonnett, NL Canfield, K Jung, VL Sprenkle, G Li. "Effect of cathode thickness on the performance of planar Na-NiCl2 battery." ***Journal of Power Sources*** 365: 456-462 (Oct. 2017).

FY18 Patents and IP

FY 18 US Patents Issued

- U.S. Patent No. ***9,960,443***, Issued May. 1, 2018. Redox flow batteries having multiple electroactive elements
- U.S. Patent No. ***9,819,039***, Issued Nov. 14, 2017. Redox flow batteries based on supporting solutions containing chloride
- U.S. Patent No. ***9,793,566***, Issued Oct. 17, 2017. Aqueous electrolytes for redox flow battery systems
- ***3 new US Patent Applications***
- ***1 new technology licenses***
- ***(32 total for technology and evaluation tools developed on PNNL OE Grid Storage Portfolio+16)***