SAND2017-12584C

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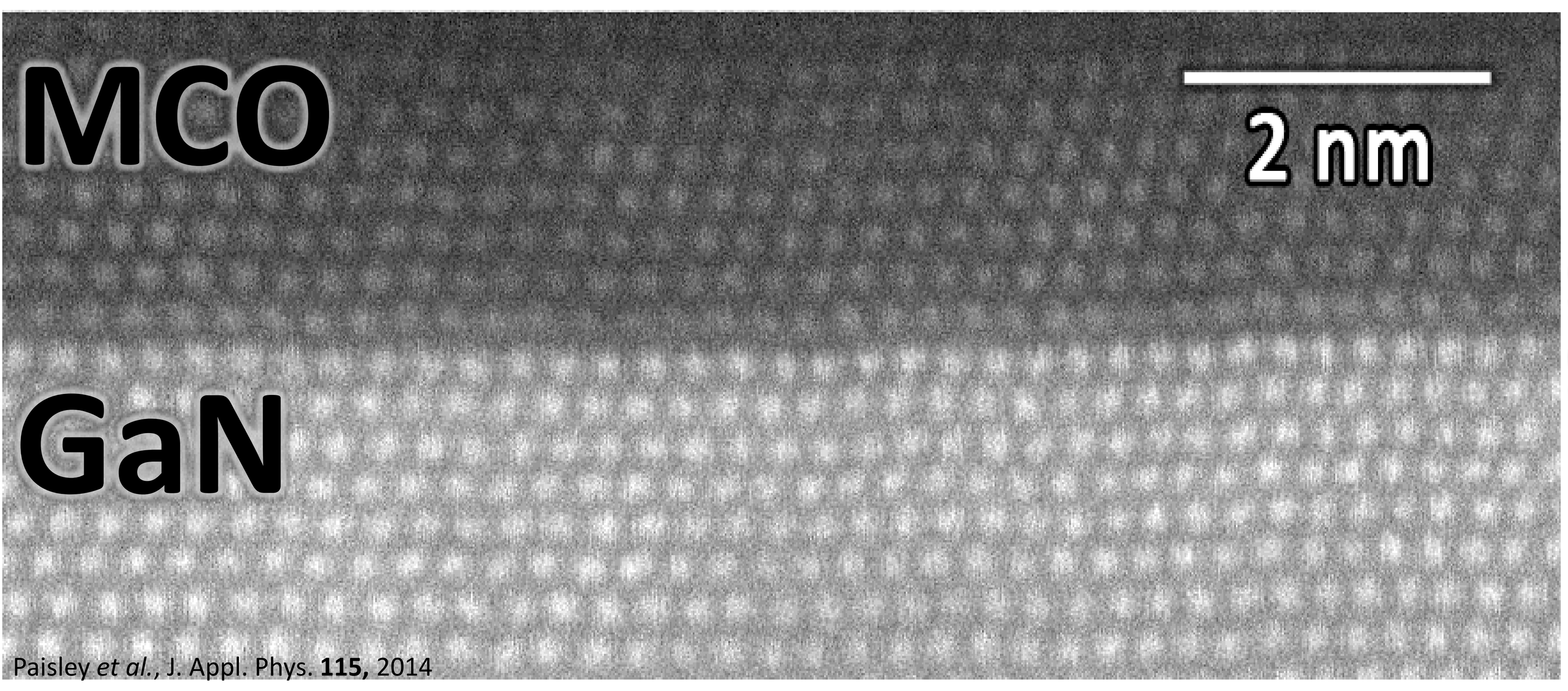
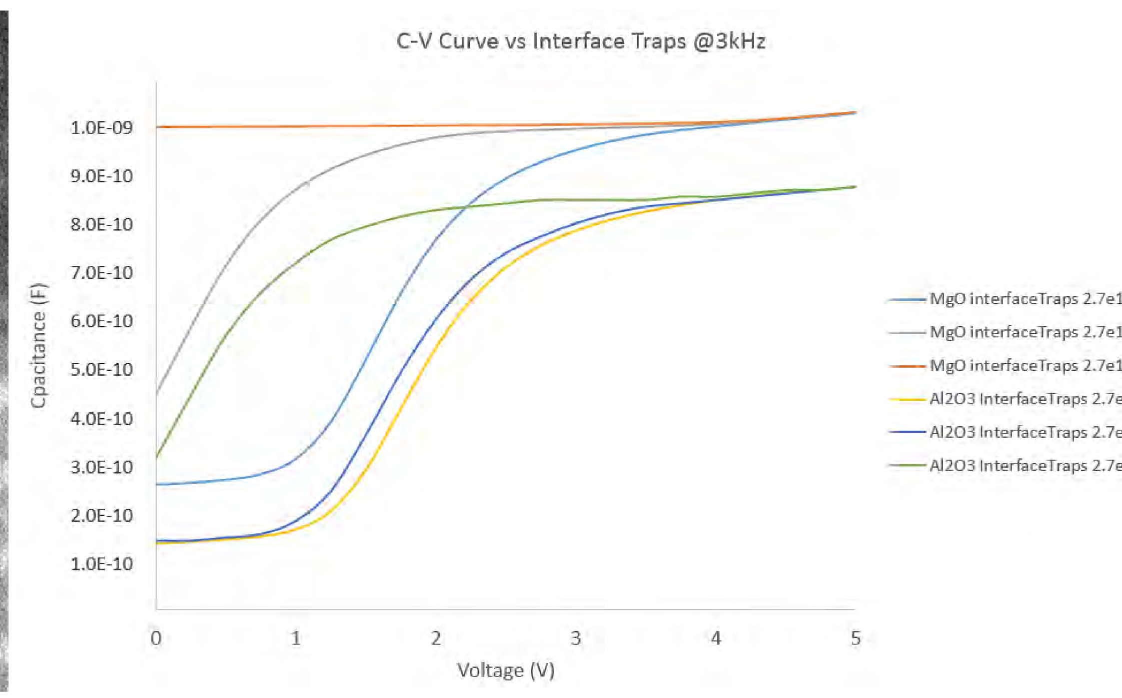
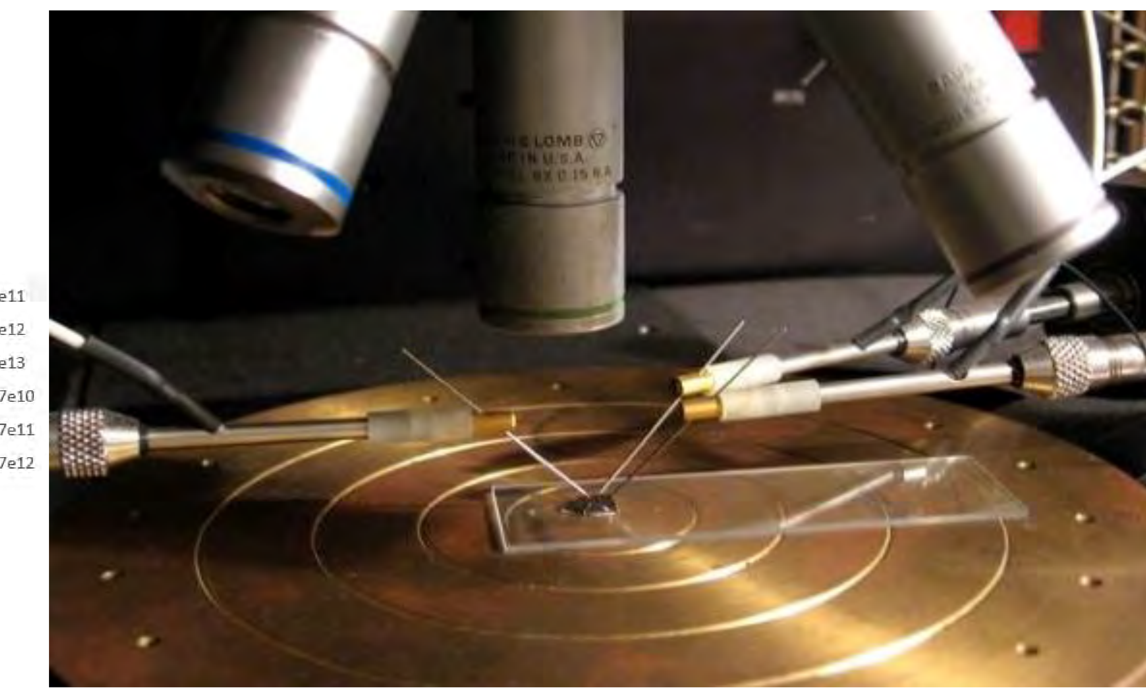
A. J. Morgan, P. Dickens, J. Ihlefeld, S. Atcitty







Gate Oxide Sentaurus Model for Wide-bandgap Devices

Motivation:

- Wide-bandgap (WBG) devices offer system level benefits to power conversion systems (PCS) for grid-tied energy storage systems (ESS)

Objective:

- Reliability is achieved through stability on the atomic level, therefore need cohesive materials, capable of operating under high-stress environments, for WBG devices (SiC, GaN)
- Weak-link for WBG MOSFETs is the gate oxide. Desire high quality oxide material(s) → low interface state density (D_{it})
- Validate measured D_{it} using a TCAD spatial solver to simulate the MgO/GaN material stack of experimental MOSCAP structures

Accomplishments:

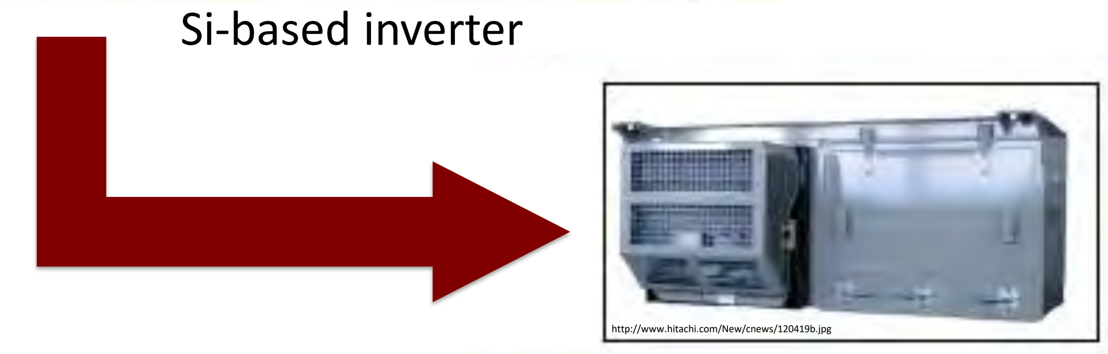
- Reproduced measured D_{it} via device-level MOSCAP models for Al_2O_3 & MgO
- Parameter script and command files created for Sentaurus material library
- Confirms most effective gate oxide on GaN to date

Potential Impact:

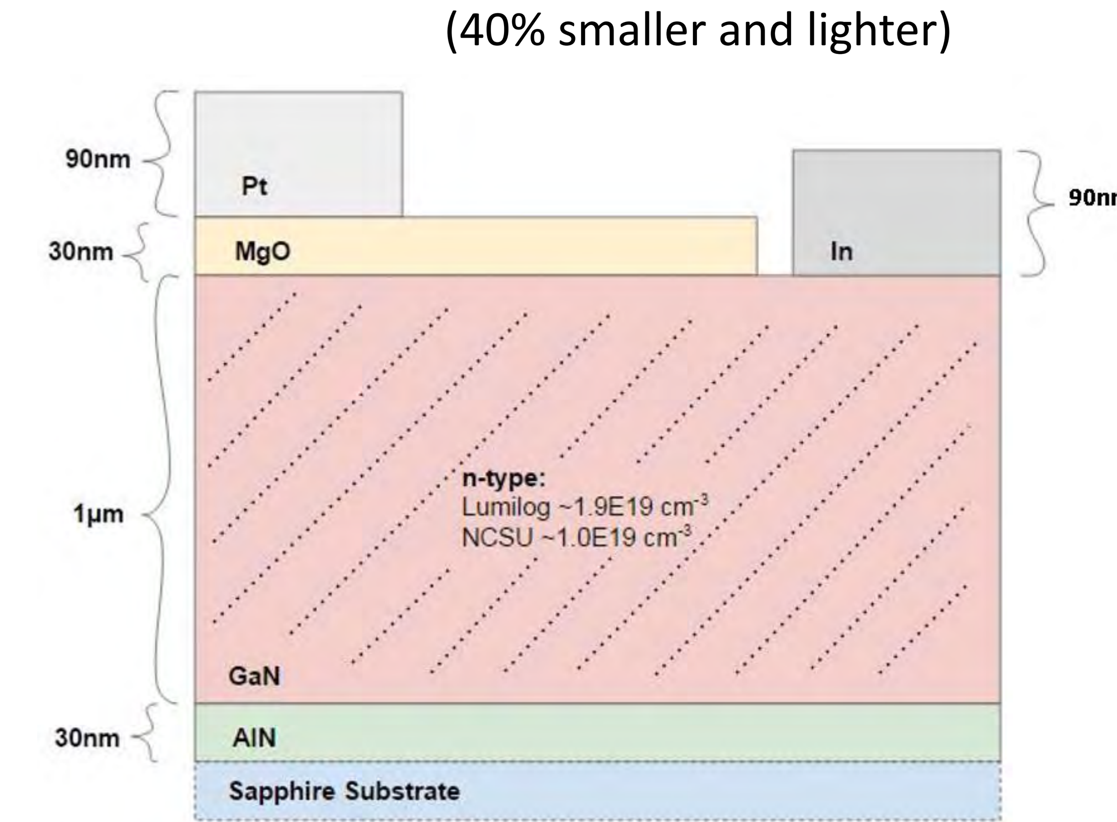
- Offers reliable, intimate control for more robust PCS for ESS material
- Predictive-analysis, simulation-first approach for exploration of new gate oxide materials on WBG semiconductors

10 kW - Cost Comparison	Silicon	WBG
Semiconductors	5% of BOM	18% of BOM
Total System	\$161.40	\$137.19 (15% less)

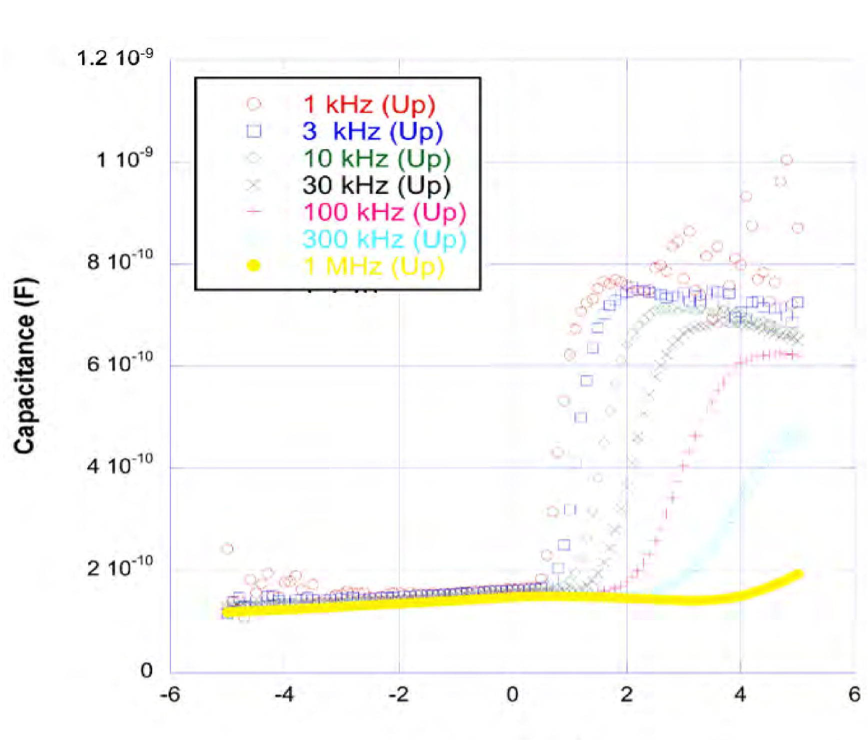
Si-based inverter



SiC hybrid module-based inverter (40% smaller and lighter)



Side-view of MOSCAP structure

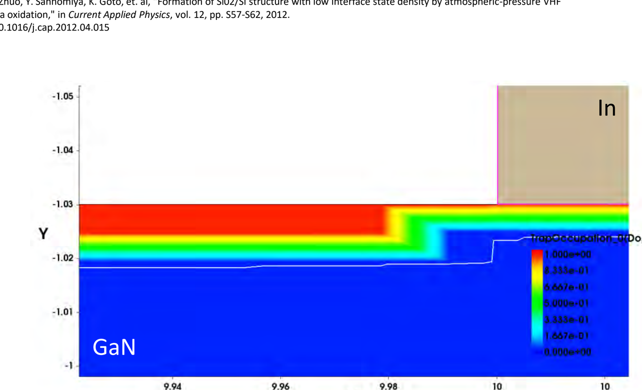


C-V measurements for MgO-based MOSCAP

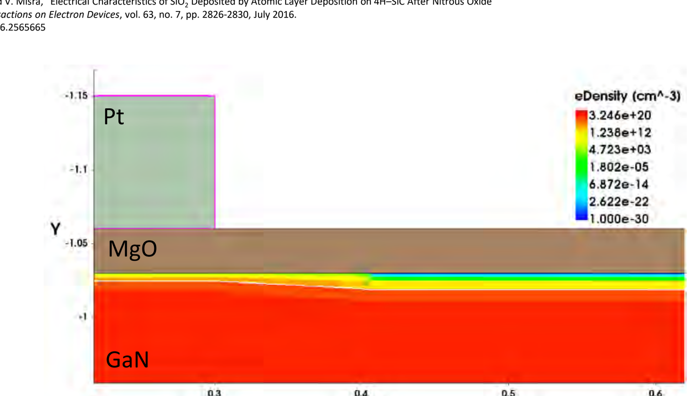
Material Interface	D_{it} ($cm^{-2}eV^{-1}$)
Si / SiO_2	1.4×10^{10} [1]
4H-SiC / SiO_2	9.0×10^{10} [2]
GaN / MgO	2.7×10^{11} [SNL]

[1] Z. Zhuo, Y. Sannomiya, K. Goto, et. al, "Formation of Si02/Si structure with low interface state density by atmospheric-pressure VHF plasma oxidation," in *Current Applied Physics*, vol. 12, pp. S57-S62, 2012. doi: 10.1016/j.cap.2012.04.015

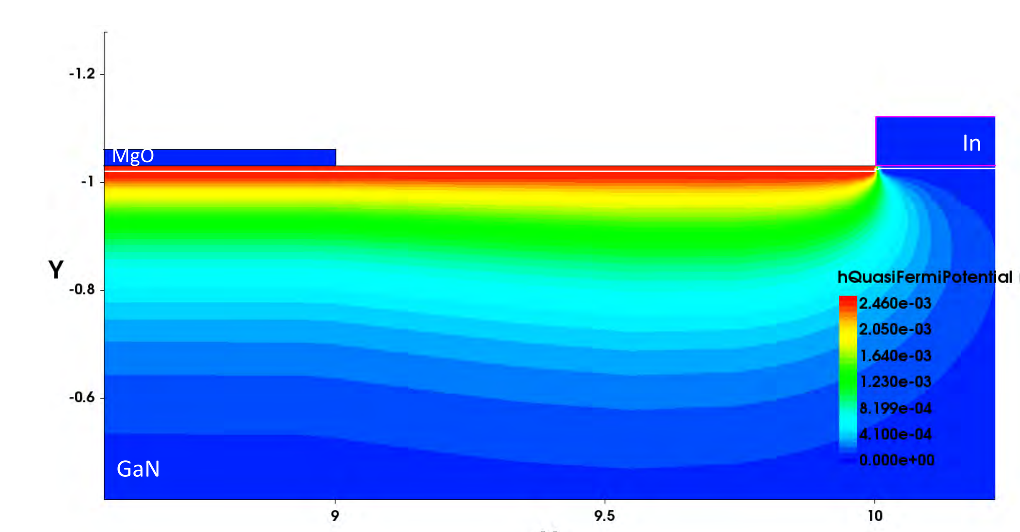
[2] X. Yang, B. Lee and V. Misra, "Electrical Characteristics of SiO_2 Deposited by Atomic Layer Deposition on 4H–SiC After Nitrous Oxide Anneal," in *IEEE Transactions on Electron Devices*, vol. 63, no. 7, pp. 2826-2830, July 2016. doi: 10.1109/TED.2016.2565665



MOSCAP trap occupation



Electron density under DC bias



Quasi fermi potential for MgO-based MOSCAP

U.S. DEPARTMENT OF ENERGY
NNSA National Nuclear Security Administration

We thank Dr. Imre Gyuk and the DOE Office of Electricity Energy Storage Program for funding this work

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https://www.dynapowerenergy.com/productoverview/dynapower-energy-storage-inverter-projects/

http://www.crks.org/wp/?page_id=1600

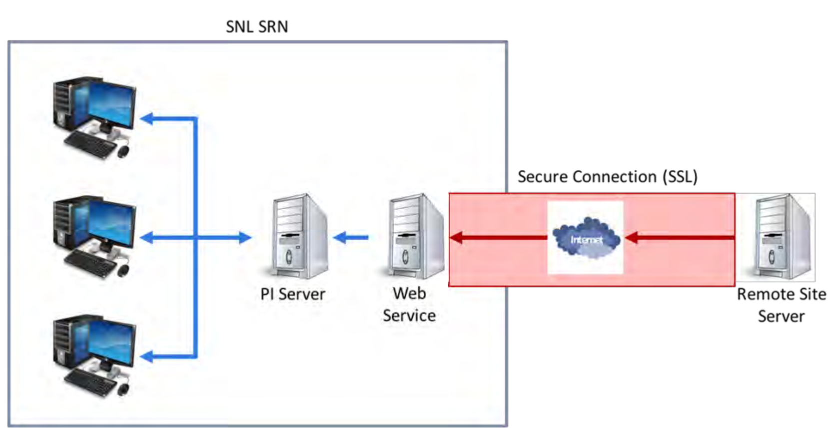
https://wwwhttps://www.ngk.co.jp/nas/case_studies/.ngk.co.jp/nas/case_studies/

Sandia's Energy Storage Projects Status

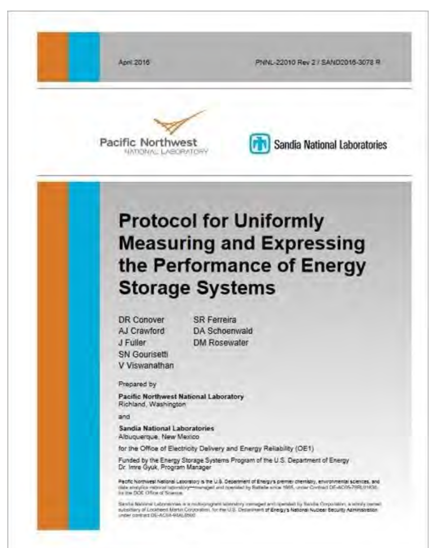
Benjamin Schenkman (Sandia), Daniel Borneo (Sandia), Lee Rashkins (Sandia), Michael Starke (ORNL), Patrick Balducci (PNNL), Marc Mueller-Stoffels (ACEP), Todd Olinsky-Paul (CESA)

Objective

Collaborate with industry, utilities, universities and other national labs to design, install, demonstrate and quantify the benefits of energy storage.



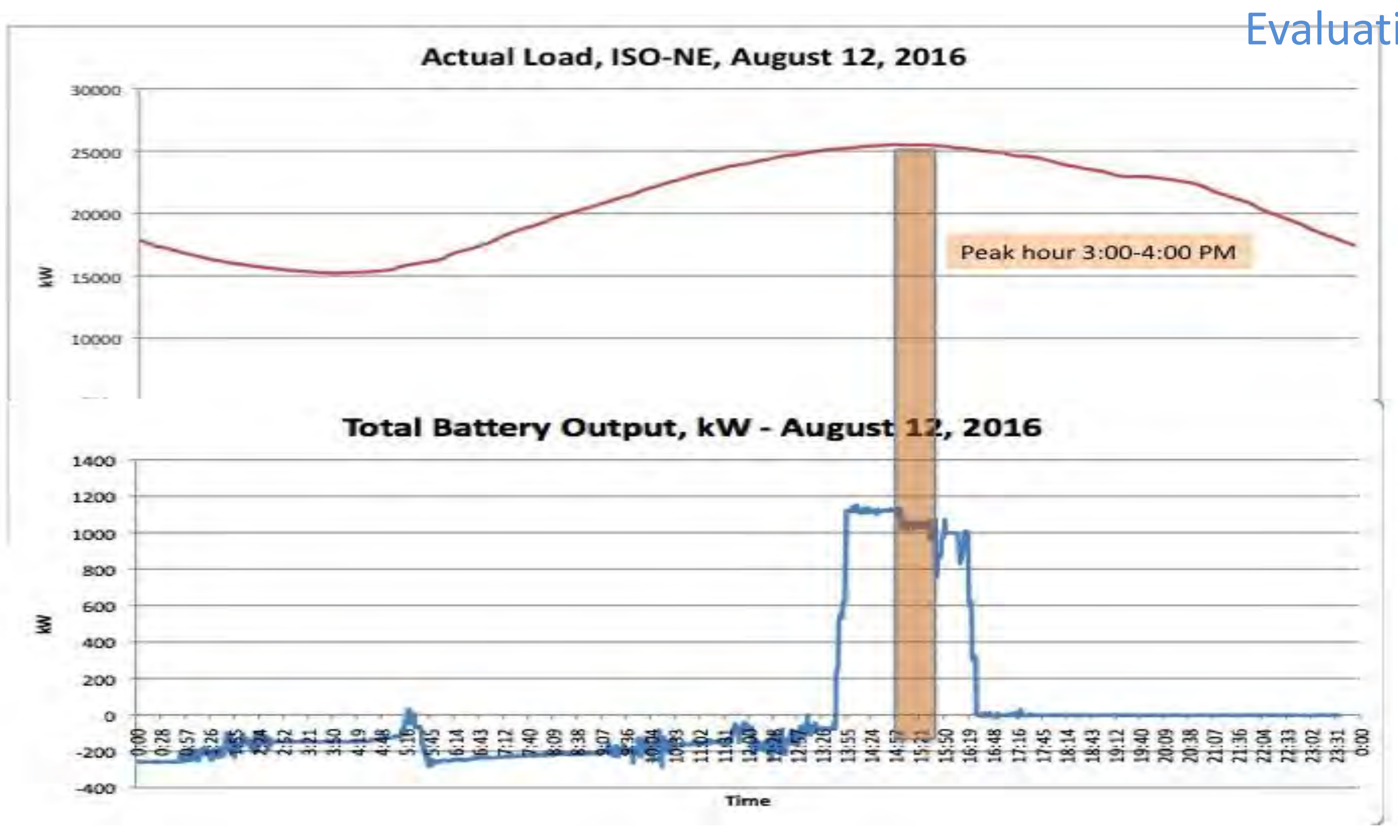
SSL Connection using entity Web Portal



PNNL/SNL ES Performance Evaluation

List of Projects

- Cordova Alaska Energy Storage Analysis with Alaska Center for Energy and Power
- Electric Power Board Vanadium Redox Flow Battery Demonstration and Performance Analysis with Oak Ridge National Lab (100kW/250kWh)
- Green Mountain Power Li-Ion/Lead Acid Performance Analysis (4MW/3.4MWh)
- Salem Smart Power Center Application Analysis of Li-Ion with Pacific Northwest National Lab (5MW/1.25MWh)
- Los Alamos County Non-Spinning reserve Analysis (1MW/6MWh NAS and 0.8MW/2.4MWH Lead)
- Natural Energy Laboratory of Hawaii Authority install and evaluation of Flow Battery and Li-Ion (100kW/250kWh)
- City of Burlington Electric energy storage for microgrid application analysis and request for proposal development



Metered Peak Shaving from GMP

Future Research and Demonstrations

- Continue collecting data from demonstration sites to evaluate performance, validate economic and technical models
- Refine energy management controls to optimize energy storage current and future applications
- Deploy more energy storage systems in various sizes, technologies and environmental conditions to increase data base and knowledge of performance limitations

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SAND2017-10724C

High Performance Sodium Cathode Materials from Their Lithium Counterparts

Biwei Xiao, Jianming Zheng, Kee Sung Han, Junhua Song, David Reed, Vince Sprenkle and Xiaolin Li*

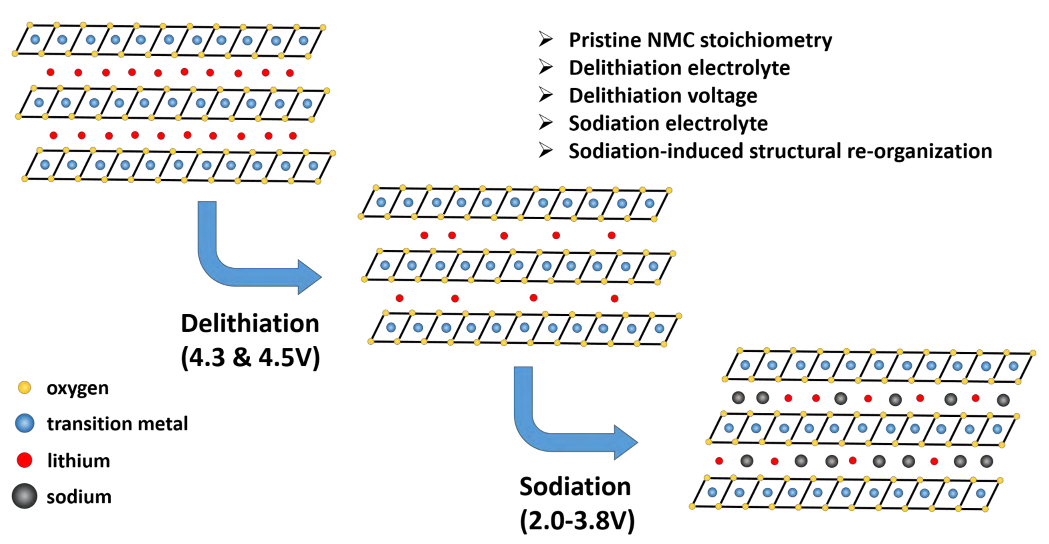
Pacific Northwest National Laboratory, Richland, WA 99352

Introduction: The quest of high-performance cathode materials for SIBs remains elusive because of the large size of sodium ions, which cause intricate structural changes such as stacking faults and sodium ion coordination adjustment. In this study, we utilized the well-known layered $LiNi_xMn_yCo_zO_2$ (NMC) Li-on batteries cathode materials as sodium intercalation host. By tuning the de-lithiation level, the cathode material stoichiometry and the electrolyte used for de-lithiation and sodiation, we were able to find an advanced electrolyte (A.E.) that enables high capacity and stability cathode material performance for SIBs.

Objectives and Methodology:

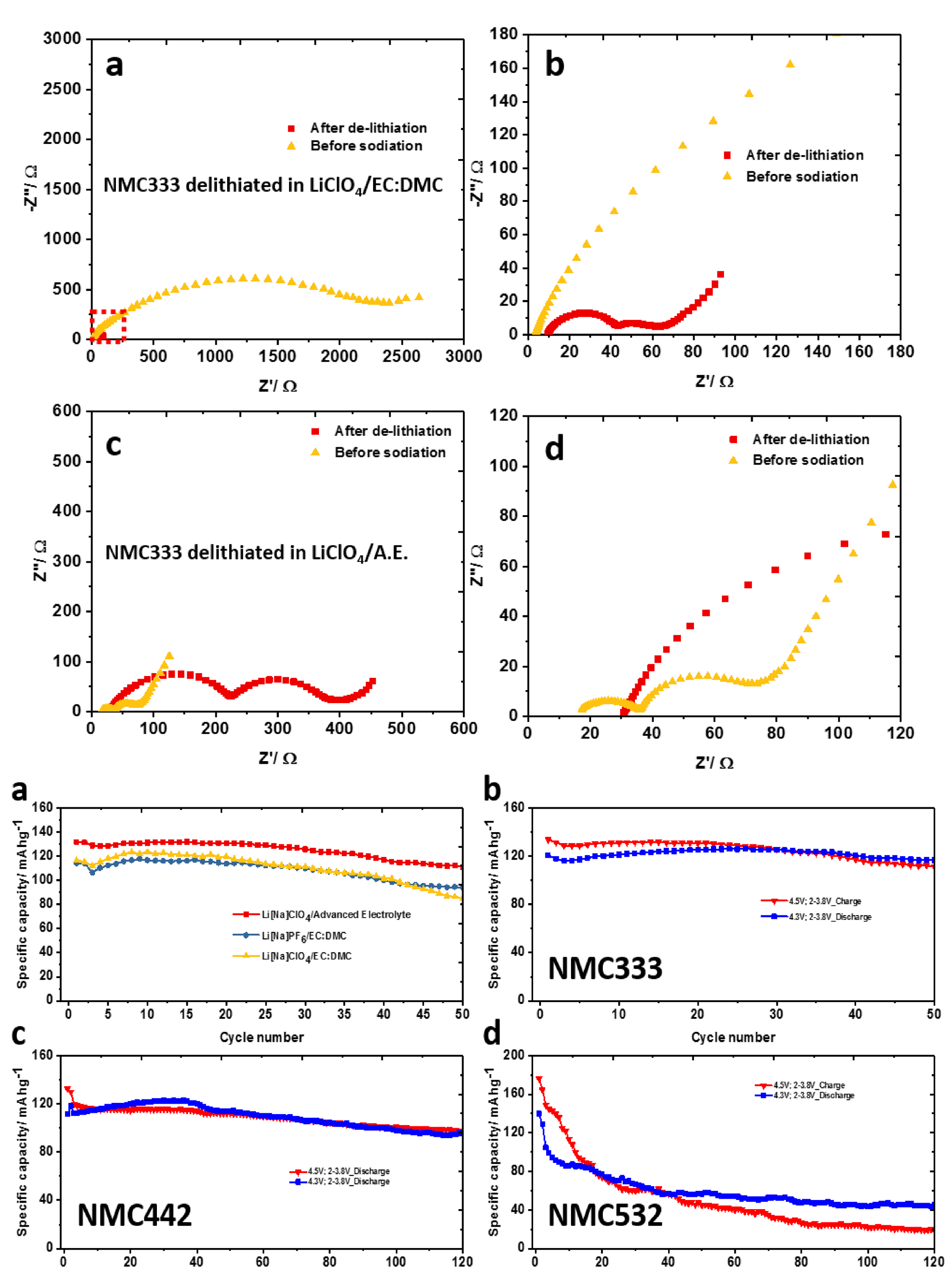
Fundamental understanding of the structural difference of Li- and Na-ion battery and practical design/synthesis of Na-ion battery cathode materials.

- ❑ High specific capacity
- ❑ High working voltage
- ❑ High cycling stability



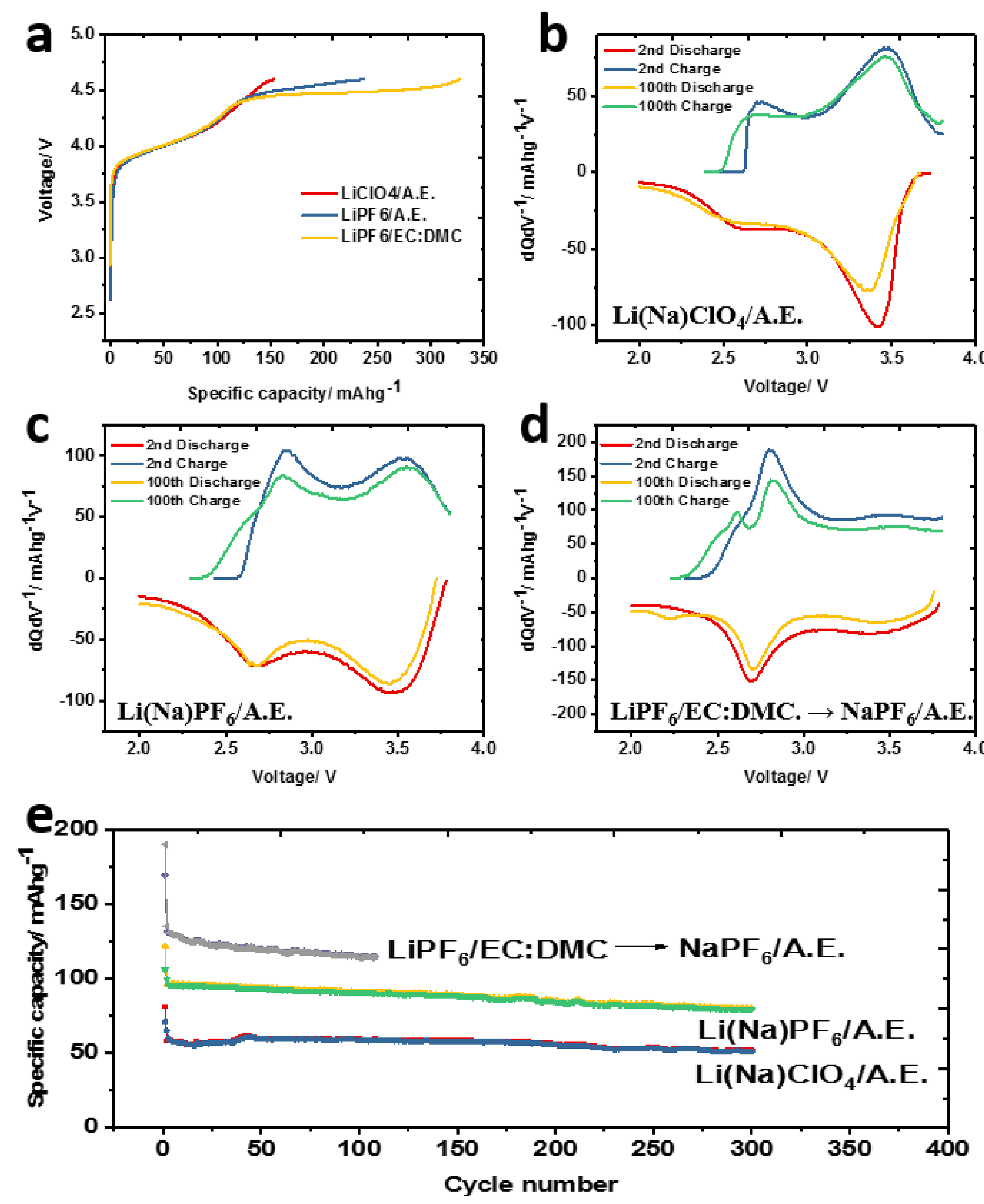
Results and Discussion:

Achievement 1) Advanced Electrolyte for NMC De-lithiation and Sodiation and Optimization of Transition Metal Stoichiometry



- ➢ Small cell impedance for the cathode material in advanced electrolyte
- ➢ High specific capacity and good cycling stability for the cathode material from lithium cathode NMC442

Achievement 2) High Performance SIBs Cathode from Li-rich NMC



- ➢ Cathode material from Li-rich NMC shows a high specific capacity of ~130 mAhg^{-1} with >85% capacity retention over 100 cycles.
- ➢ The capacity is mainly from the Na intercalation into the lithium layer and there is no voltage fade over 100 cycles.

Summary and Perspective:

- ❑ The de-lithiation and sodiation of layered lithium cathode materials was realized by using the advanced electrolyte, which does not present significant impedance to sodium transportation across the material surface.
- ❑ The stoichiometry of transition metals have been explored and an optimum combination has been proposed.
- ❑ Remaining lithium ions in the sodium ions layer is beneficial to the stability of the sodiation/de-sodiation process.
- ❑ The de-lithiation level of Li-rich NMC demonstrates different sodium intercalation behaviors, which should be associated with two different Li sites.

Future Work

- ❑ Understanding the role of the remaining Li in improving the stability using advanced characterization techniques.
- ❑ Improving the performance of the sodiation of de-lithiated layered lithium cathode materials by adjusting the structure.
- ❑ Direct synthesis of the corresponding sodium cathode materials with the optimized stoichiometry obtained

Acknowledgements

This work is supported by the U.S. Department of Energy (DOE) Office of Electricity Delivery and Energy Reliability under contract No. 57558. PNNL is a operated by Battelle Memorial Institute for the DOE under contract DE-AC05-76RL01830

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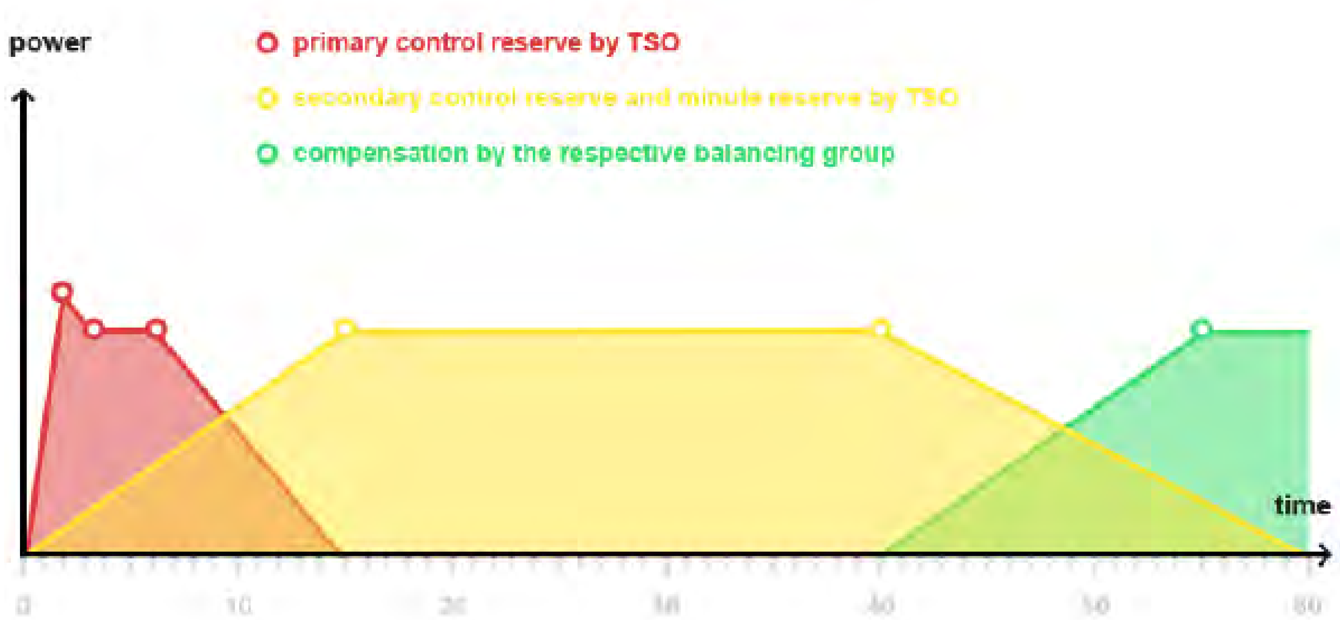
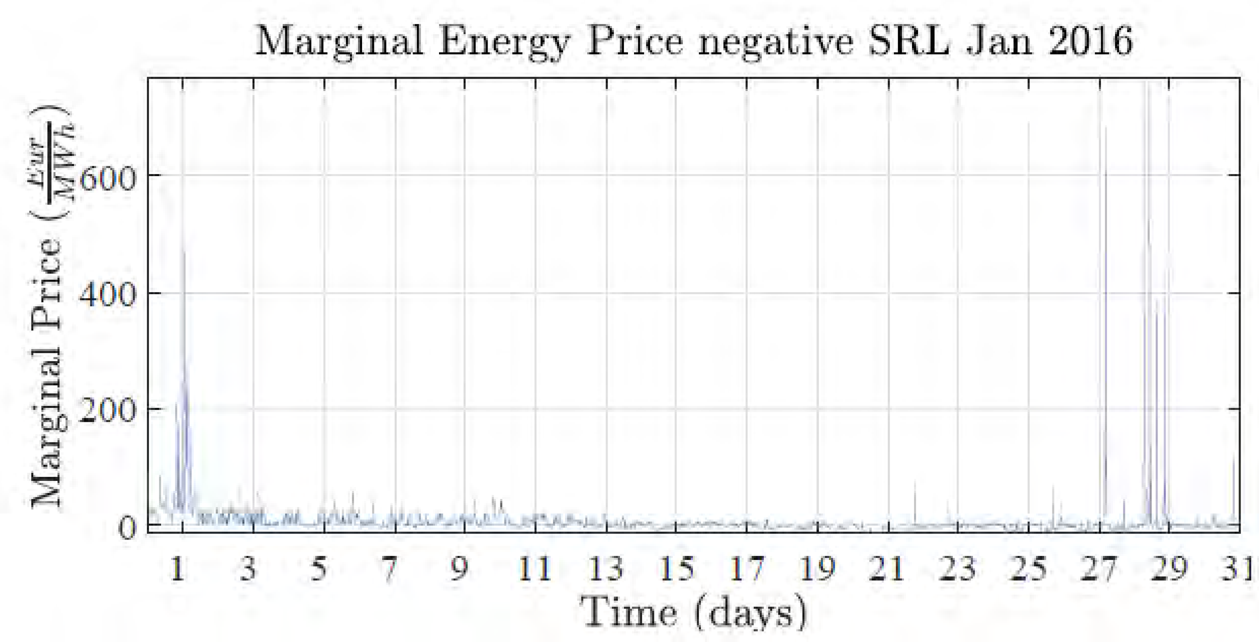
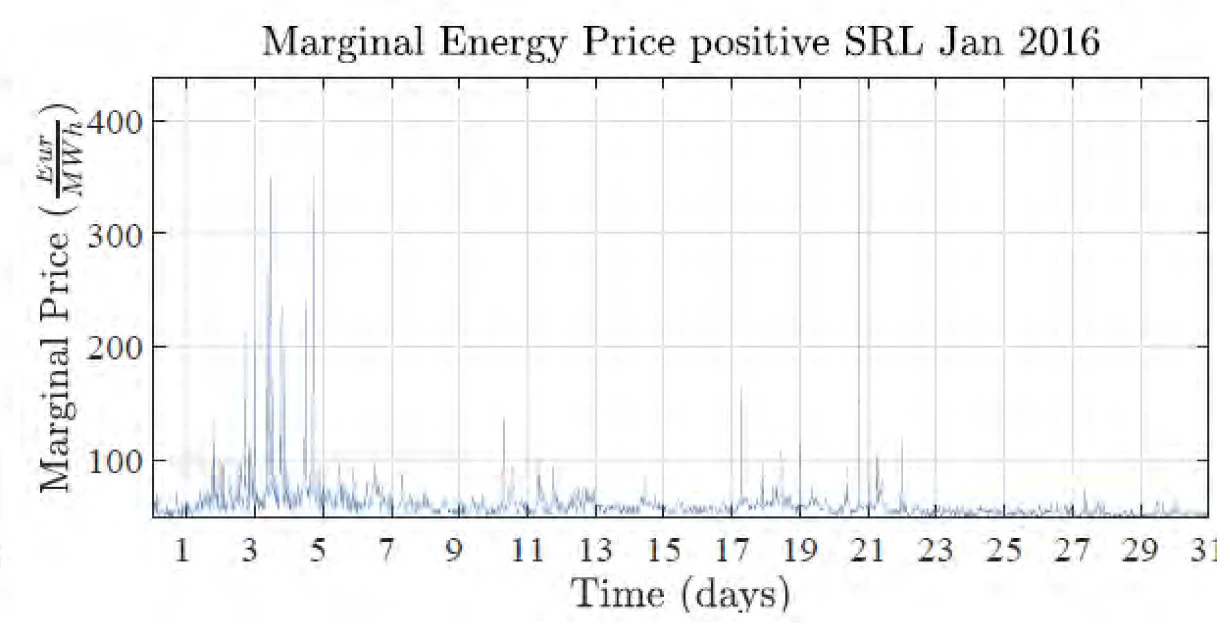
References:

1. M. H. Han et al., *Energy Environ. Sci.*, 2015. 8. 81
2. X. Xiang et al., *Adv. Mater.*, 2015, 27, 5343
3. P. Wang et al., *Adv. Mater.*, 2017, 29, 1700210







Energy Storage Participation in the German Secondary Regulation Market

Christoph Lackner, Tu Nguyen, Raymond H Bryne, Frank Wiegandt

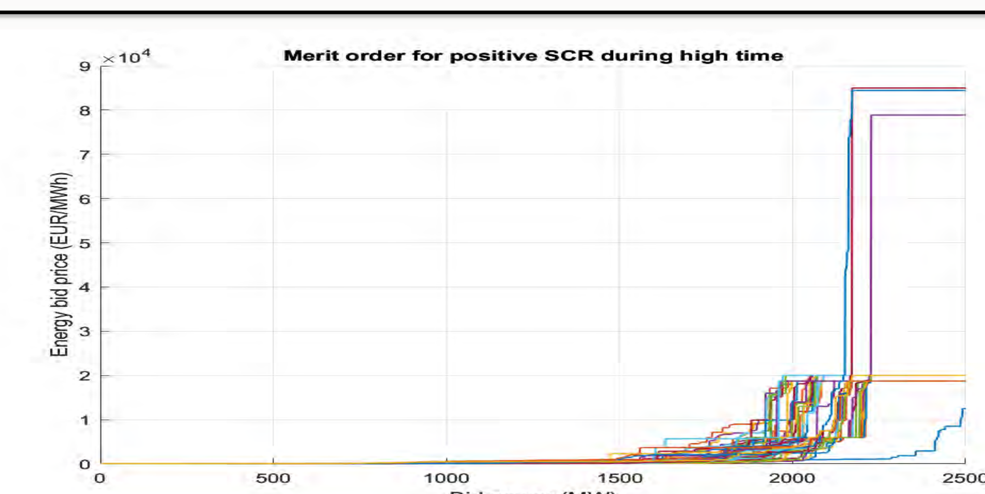
Email: lacknc@rpi.edu, tunguy@sandia.gov, rhbyrne@sandia.gov, frank.wiegandt@wwfsolar.de

Abstract

This work investigates the potential of Battery Energy Storage systems in the German secondary frequency regulation (SCR) market. A case study is conducted to investigate the revenue opportunity of a 48 MWh Battery System participating in SCR.

German Frequency Regulation Market: consists of 3 parts with positive and negative product each

- Primary Frequency Regulation (PRL)
- Secondary Frequency Regulation (SRL)
- Tertiary Frequency Regulation (MRL)



	positive SRL	negative SRL
Mean ($\frac{Eur}{MWh}$)	50.27	3.72
Minimum ($\frac{Eur}{MWh}$)	29.80	−22.10
Maximum ($\frac{Eur}{MWh}$)	6000.00	3990.00

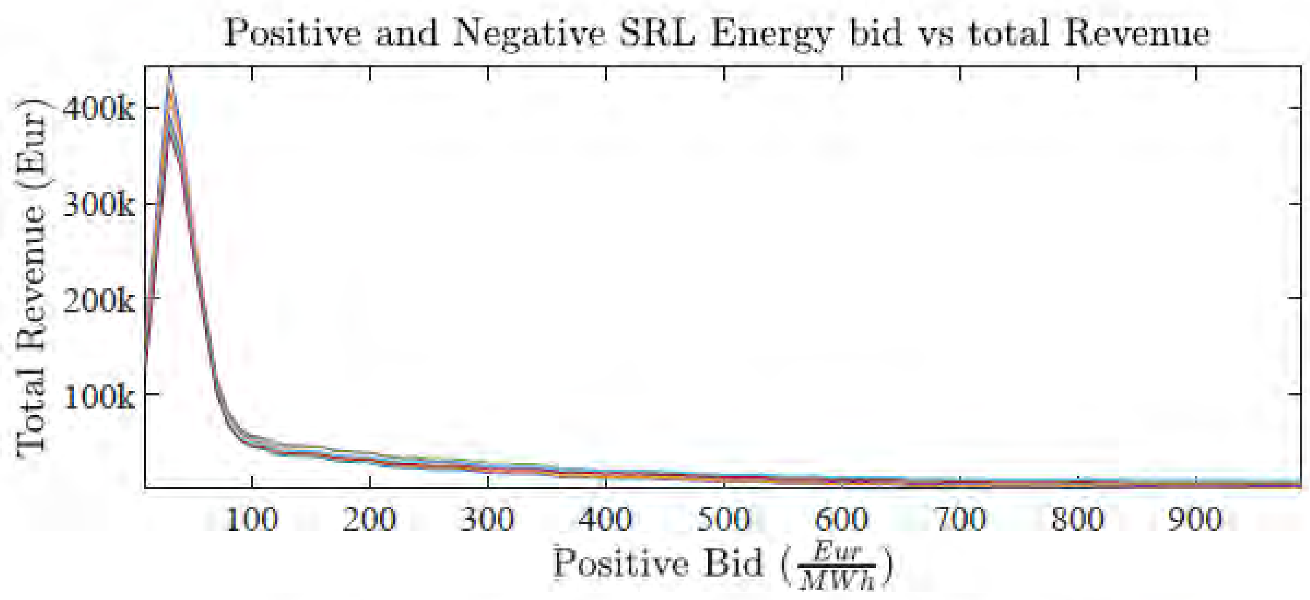
Table 1: Statistics of SRL Market in 2016

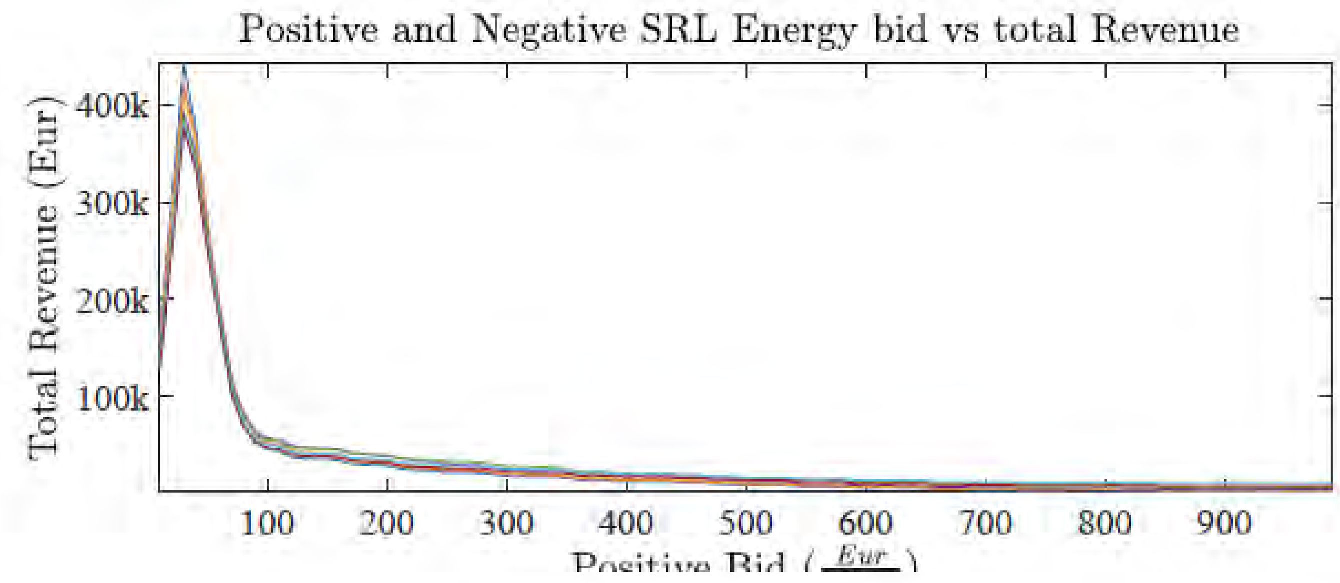
Case Study:

- Battery System in Table 2 was simulated using historical SRL market data from 2016
- A constant *Energy and Capacity Bid* was assumed
- SOC management was considered since more than 3 violations in 1 week lead to market disqualification

Characteristic	Value
Charging efficiency	0.7
Storage Capacity	48 MWh
Power rating	12MW

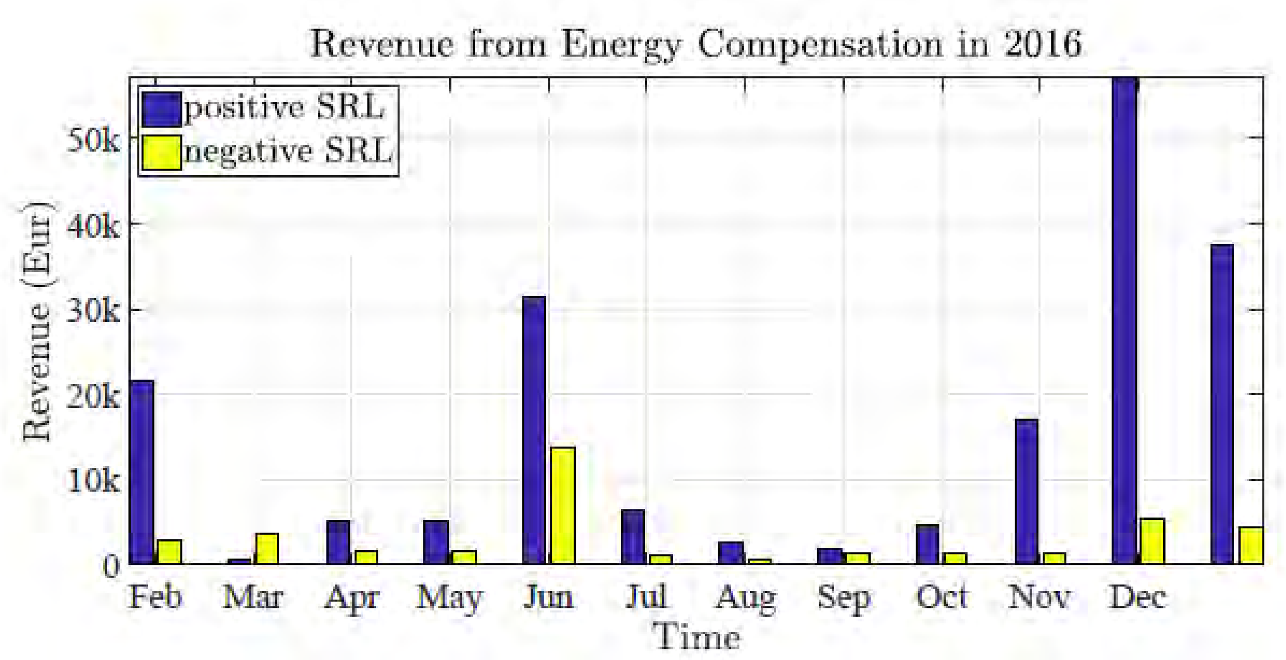
Table 2: Characteristic of Battery System

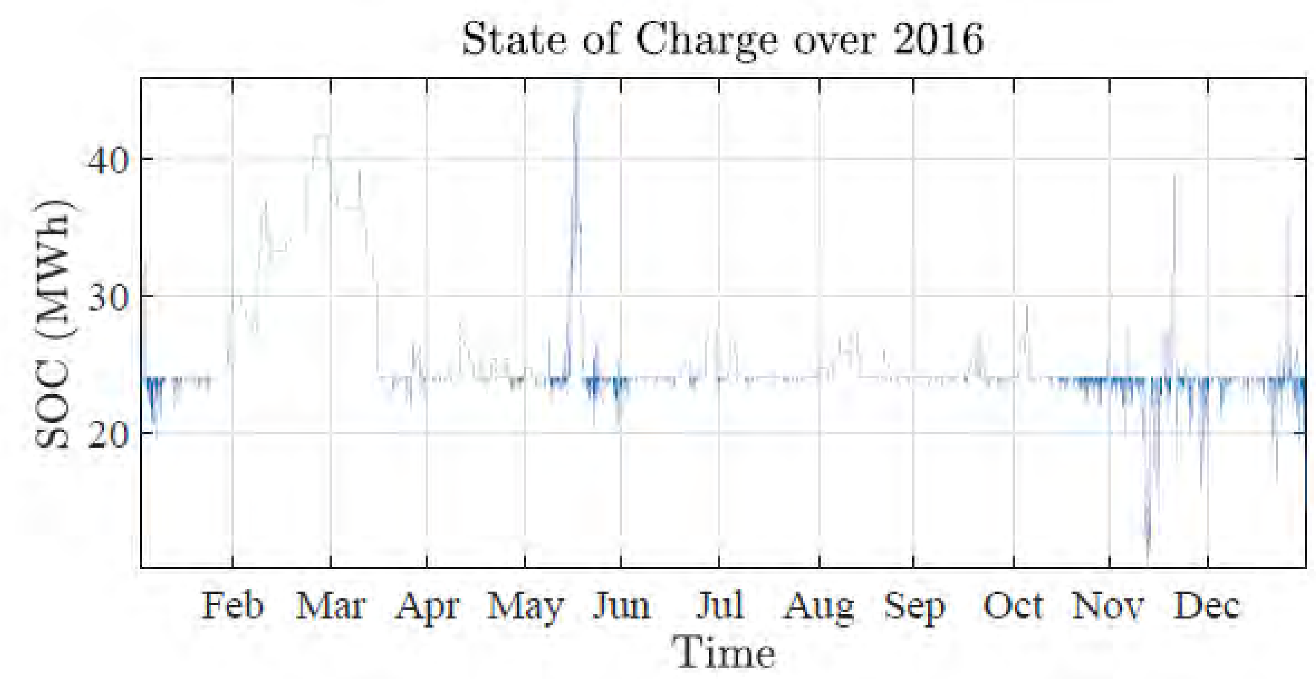


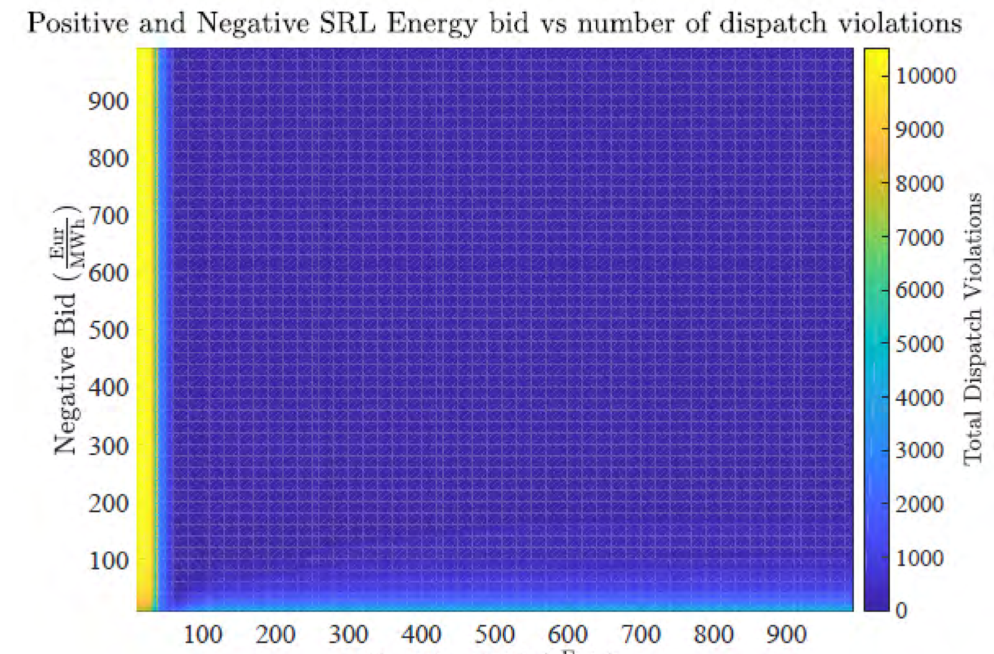


Capacity		7,488 Eur
Energy	positive HT	111,580 Eur
	positive NT	81,620 Eur
	negative HT	13,130 Eur
	negative NT	26,130 Eur

Table 3: Revenue from Capacity and Energy Compensation







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Energy Storage Data Submission Guidelines

Cole Benson and Ben Schenkman

Objective

Often times some Energy Storage System data is inconsistent and incomplete which leads to inefficacy of the data when it comes time to analyze. These data guidelines aim to remedy this issue by providing the necessary data points and sampling rates. High quality data will allow the industry to better understand energy storage systems and allow for faster and more robust data analysis.

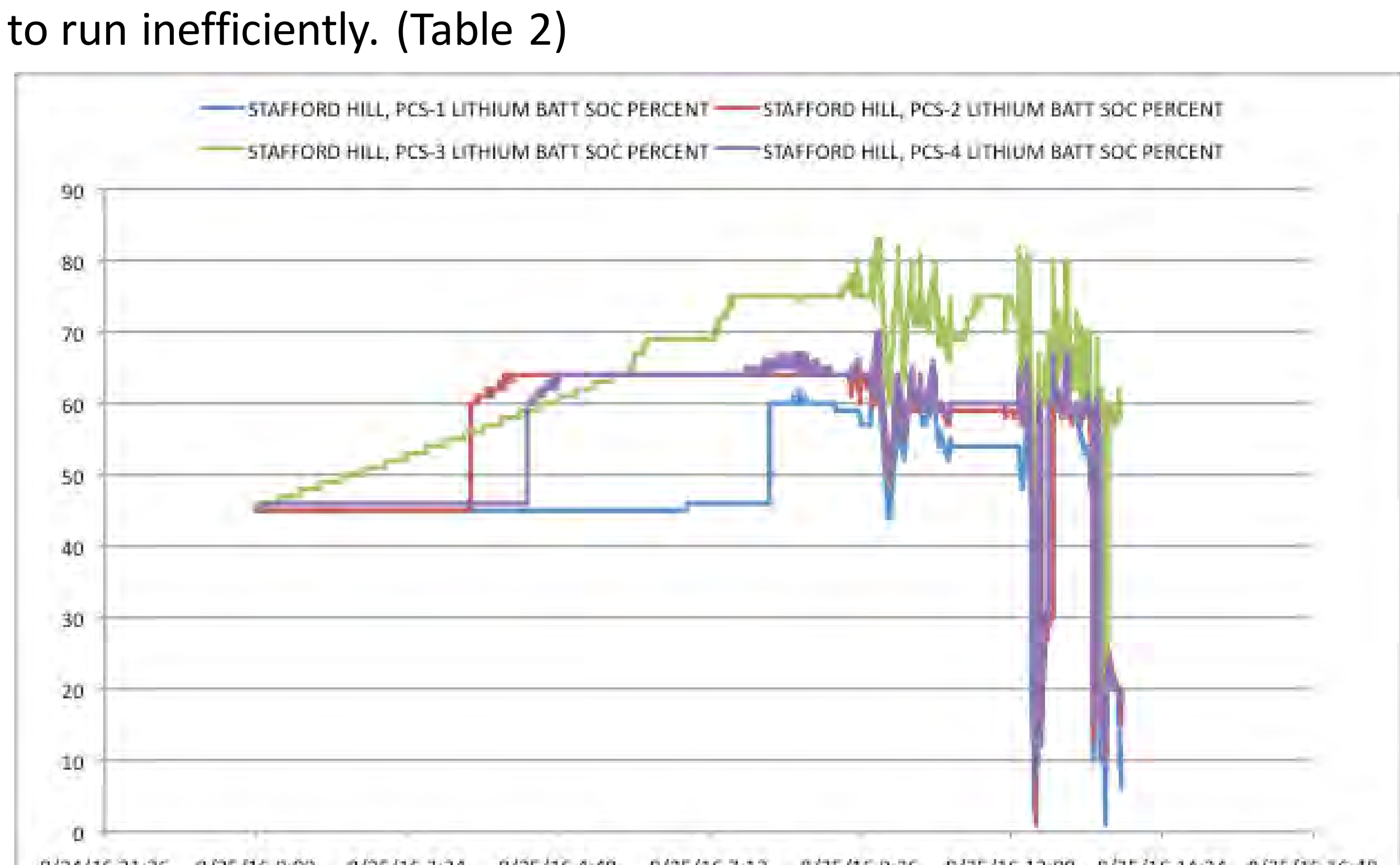
Data Points

Electrical AC Data and Conditions Points

The AC data points are important as they inform the engineer the amount of power coming in and out of the system. With these data points they can find important system statistics that indicate what the system is putting back into the grid as well as overall roundtrip efficiencies, power quality, and capacity fade. In addition, environmental and energy market points are useful because they allow the engineer to see the conditions the system is operating in and how these conditions affect the system. Financial market conditions like electricity price/cost are also included in this set as they help with the economic analysis of the system and its feasibility. (Table 1)

Specific Cell Data Points

While it is important to see how the entire system performs as a whole, it is also useful to see how each cell is behaving within the system, especially from a safety standpoint. By having access to each cell, the engineer can determine if a cell is impacting the system efficiency and if a cell is more likely to lead to safety concerns such as thermal runaway. DC data points for each cell are important as well because they can be used as a barometer of each cell's "health" and to pinpoint which cell could be causing the system to run inefficiently. (Table 2)



Data taken from Green Mountain Power's Stafford Hill 4MW/3.4MWh battery energy system

https://cesa.org/assets/Uploads/SAND2017-6164.pdf

Future Perspectives

-Integrate these data points into monitoring an active energy storage system to create an interface that displays each of these points in real time

-After usage in the monitoring of energy storage systems, refine the data points included based on the data analysis performed

System Data Points

Point	Sample Rate Minimum	Power Application Report Out Minimum	Energy Application Report Out Minimum	Values
AC Real Power	≥1 Sample/Second	≥1 Sample/Second	≥ 1 Sample/15 minutes	value, max, min, avg
AC VAR	≥1 Sample/Second	≥1 Sample/Second	≥ 1 Sample/15 minutes	value, max, min, avg
AC Voltage	≥1 Sample/Second	≥1 Sample/Second	≥ 1 Sample/15 minutes	value, max, min, avg
THD	≥500 Samples/Second	≥1 Sample/Second	≥ 1 Sample/15 minutes	value, max, min, avg
Flicker	≥500 Samples/Second	≥1 Sample/Second	≥ 1 Sample/15 minutes	value, max, min, avg
System Frequency	≥1 Sample/Second	≥1 Sample/Second	≥ 1 Sample/15 minutes	value, max, min, avg
Total AC Discharge Energy	≥1 Sample/Second	≥1 Sample/Second	≥ 1 Sample/15 minutes	value, max, min, avg
Total AC Charge Energy	≥500 Samples/Second	≥1 Sample/Second	≥ 1 Sample/15 minutes	value, max, min, avg
Auxiliary Loads	≥1 Sample/Second	≥1 Sample/Second	≥ 1 Sample/15 minutes	value, max, min, avg
Outside Temperature	≥1 Sample/Minute	≥1 Sample/Minute	≥ 1 Sample/15 minutes	value, max, min, avg
% Cloud Cover	≥1 Sample/Minute	≥1 Sample/Minute	≥ 1 Sample/15 minutes	value, max, min, avg
Internal Temperature	≥1 Sample/Minute	≥1 Sample/Minute	≥ 1 Sample/15 minutes	value, max, min, avg
Electricity Price/Cost	Sample rate associated with price data	Sample rate associated with price data	Sample rate associated with price data	value
Demand Charge Structure and Load Data	≥1 Sample/Minute	≥1 Sample/Second	≥ 1 Sample/15 minutes	value
Market Structure and price/cost data	Market Data Rate	Market Data Rate	Market Data Rate	value
Events: Errors, Warnings and Faults	≥500 Samples/Second	≥1 Sample/Second	≥ 1 Sample/15 minutes	value, max, min, avg
Power Quality Events	≥500 Samples/Second	≥1 Sample/Second	≥ 1 Sample/15 minutes	value, max, min, avg
Maintenance Logs	Per manufacturer	Daily	Daily	value, max, min, avg
Operator Commands	≥1 Sample/Second	≥1 Sample/Second	≥ 1 Sample/15 minutes	value, max, min, avg
Communication Conductivity Disruptions	≥1 Sample/Second	≥1 Sample/Second	≥ 1 Sample/15 minutes	value, max, min, avg

Table 1

Cell/Pack/String Data Points

Point	Sample Rate Minimum	Power Application Report Out Minimum	Energy Application Report Out Minimum	Values
AC Real Power	≥1 Sample/Second	≥1 Sample/Second	≥ 1 Sample/15 minutes	value, max, min, avg
AC VAR	≥1 Sample/Second	≥1 Sample/Second	≥ 1 Sample/15 minutes	value, max, min, avg
DC Power	≥1 Sample/Second	≥1 Sample/Second	≥ 1 Sample/15 minutes	value, max, min, avg
DC Current	≥1 Sample/Second	≥1 Sample/Second	≥ 1 Sample/15 minutes	value, max, min, avg
DC Voltage	≥1 Sample/Second	≥1 Sample/Second	≥ 1 Sample/15 minutes	value, max, min, avg
Total DC Charge Energy	≥1 Sample/Second	≥1 Sample/Second	≥ 1 Sample/15 minutes	value, max, min, avg
Total DC Discharge Energy	≥1 Sample/Second	≥1 Sample/Second	≥ 1 Sample/15 minutes	value, max, min, avg
Min Cell Voltage	≥1 Sample/Second	≥1 Sample/Second	≥ 1 Sample/15 minutes	value, max, min, avg
Max Cell Voltage	≥1 Sample/Second	≥1 Sample/Second	≥ 1 Sample/15 minutes	value, max, min, avg
Min Cell Temperature	≥1 Sample/Second	≥1 Sample/Second	≥ 1 Sample/15 minutes	value, max, min, avg
Max Cell Temperature	≥1 Sample/Second	≥1 Sample/Second	≥ 1 Sample/15 minutes	value, max, min, avg
Min Cell Resistance	≥1 Sample/Second	≥1 Sample/Second	≥ 1 Sample/15 minutes	value, max, min, avg
Mean Cell Resistance	≥1 Sample/Second	≥1 Sample/Second	≥ 1 Sample/15 minutes	value, max, min, avg
Max Cell Resistance	≥1 Sample/Second	≥1 Sample/Second	≥ 1 Sample/15 minutes	value, max, min, avg
Events: Errors, Warnings and Faults	≥500 Samples/Second	≥1 Sample/Second	≥ 1 Sample/15 minutes	value, max, min, avg
Power Quality Events	≥500 Samples/Second	≥1 Sample/Second	≥ 1 Sample/15 minutes	value, max, min, avg
Maintenance Logs	Per manufacturer	Daily	Daily	value, max, min, avg

Table 2

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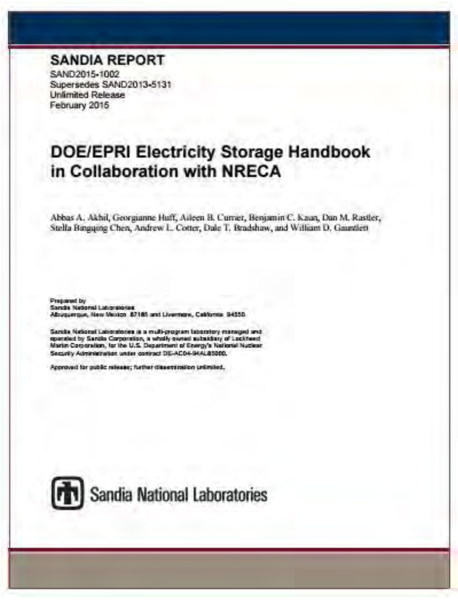
ESS ENERGY STORAGE SYSTEMS

PEER REVIEW 2017
EVOLUTION & REVOLUTION
San Diego, California | October 9-10, 2017

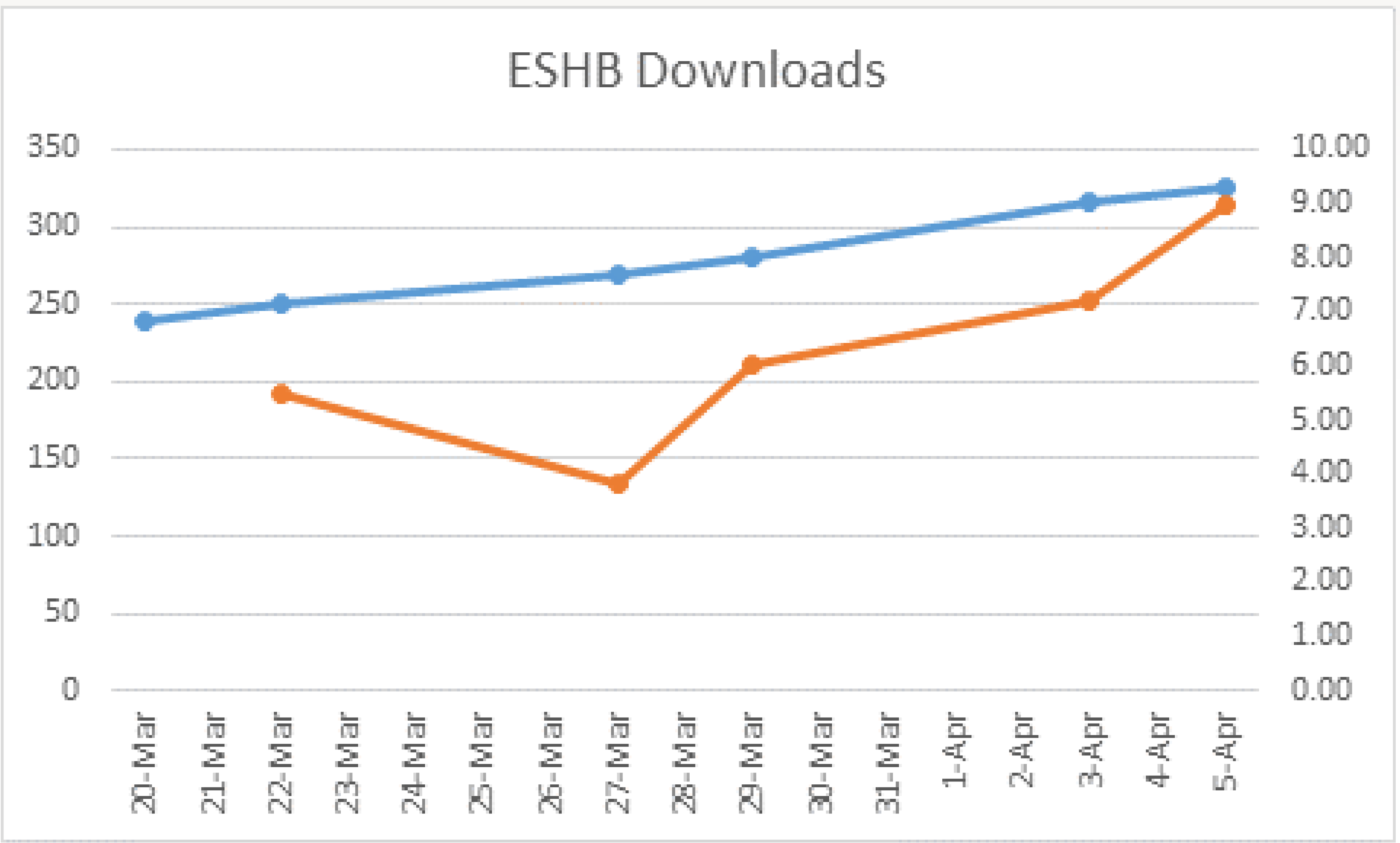


The DOE/ESS Website; Tech Conference Recruiting, & Social Media

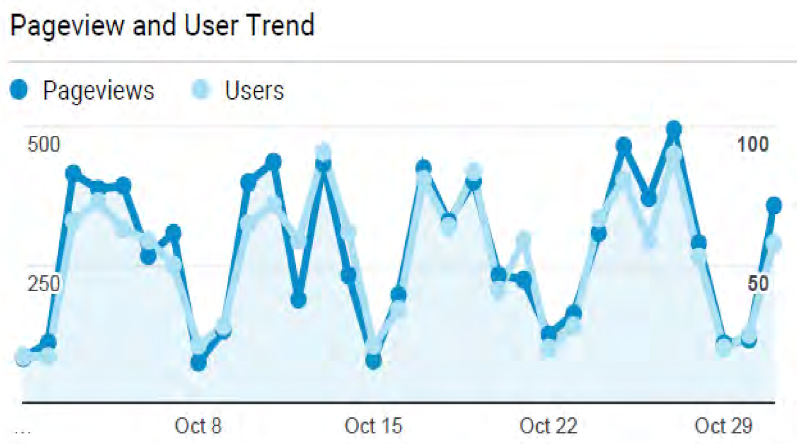
Cris Romero

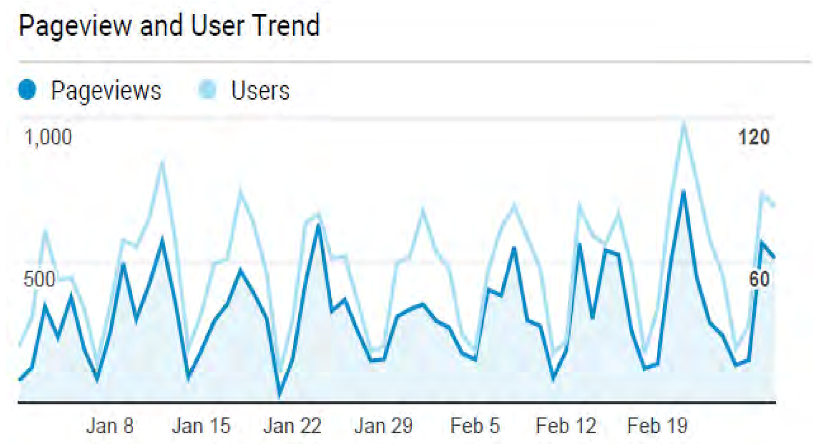
THE DOE/ESS Website – by the Numbers

Through maintaining and updating the DOE/ESS Website we can see numbers in hits, views and downloads increase. Energy Storage Handbook averages at 6 downloads per day (early 2017.) The daily average is at a steady increase in March/April 2017. Similar trends are also seen in average session times and "New Visitors" with increases from 2016 to 2017. For instance, the figure below indicates that there were 10,000 downloads of the 2016 version of the DOE/EPRI/Sandia/NRECA Electricity Handbook, called the ESHB!

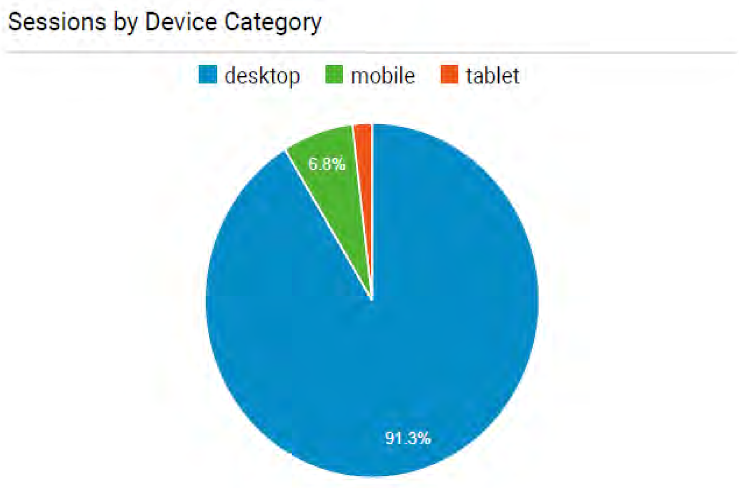


We also see an increase in page view and users from 2016 to 2017. Page views on important sites nearly double such as Publications, Journal Articles and Conference Archives.





Small trends show changes in how sessions are accessed. There is a slight decrease in access through desktop from and a slight increase in mobile access 2016 to 2017



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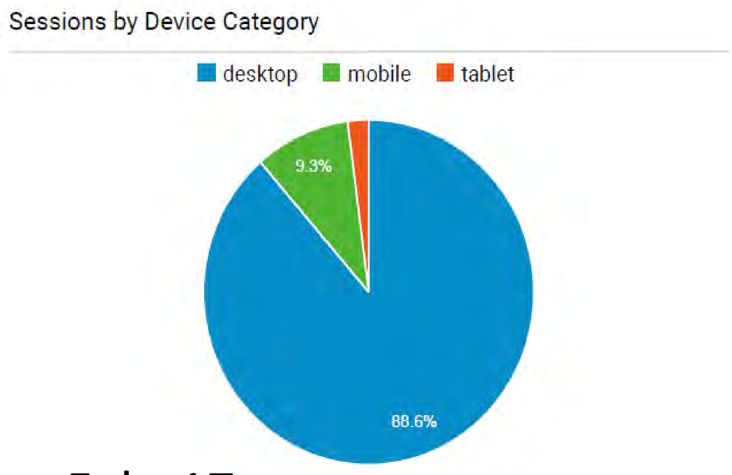

Feb. 17

As for the Millennials

Another goal for Energy Storage Strategic Outreach was to make the 2017 Peer Review & EESAT Conference accessible to people of all ages. In order to create a pipeline of the next generation of engineers, scientists, technologists, economists, etc., interested in the sciences related to energy storage, I led the project that resulted in on-site recruiting at an energy storage technical conference.

Reaching and mobilizing undergraduate and graduate students relied heavily on social media tactics. Engaging with students through the web allowed for a broad reach of individuals. By utilizing social media we are able to disseminate materials more efficiently and cost effectively.

Creating an official hashtag, #EESAT 2017, allows for participants to join conversations online and stay connected

Energy

@Sandiaenergy

Thank you Dr. Imre Gyuk for your funding support. We continue to find new ways to reach out and share the mission and goals of the DOE/OE Energy Storage Program.

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NNSA National Nuclear Security Administration

Impact of Frequency Regulation on Degradation of Commercial Li-ion Batteries

Daiwon Choi, Alasdair J. Crawford, Vilayanur V. Viswanathan, Qian Huang, Michael CW. Kintner-Meyer, Ji-Guang Zhang, David M. Reed, Vince L. Sprenkle

Pacific Northwest NATIONAL LABORATORY

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Abstract

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.[1] This study describes how two different Li-ion battery chemistries based on $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$ (NCA) and $LiFePO_4$ (LFP) cathodes were tested under grid duty cycles recently developed for two specific grid services: (1) frequency regulation[2,3] (FR) and (2) peak shaving[2] (PS) with and without being subjected to electric vehicle (EV) drive cycles. The lifecycle comparison derived from the capacity, round-trip efficiency (RTE), resistance, charge/discharge energy, and total used energy of the two battery chemistries are discussed. The LFP chemistry shows better stability for the energy-intensive PS service, while the NCA chemistry is more conducive to the FR service under the operating regimes investigated. The results can be used as a guideline for selection, deployment, operation, and cost analyses of Li-ion batteries used for different applications.

Experimental

- **High-energy $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$ - Graphite (NCA):** 3.2Ah 18650 cylindrical, 2.5 - 4.2 V, C/2 charge/4C max. discharge.
- **High-power $LiFePO_4$ - Graphite (LFP):** 2.6Ah 26650 cylindrical, 2.0 - 3.6 V, 1 C charge/20C max. discharge.

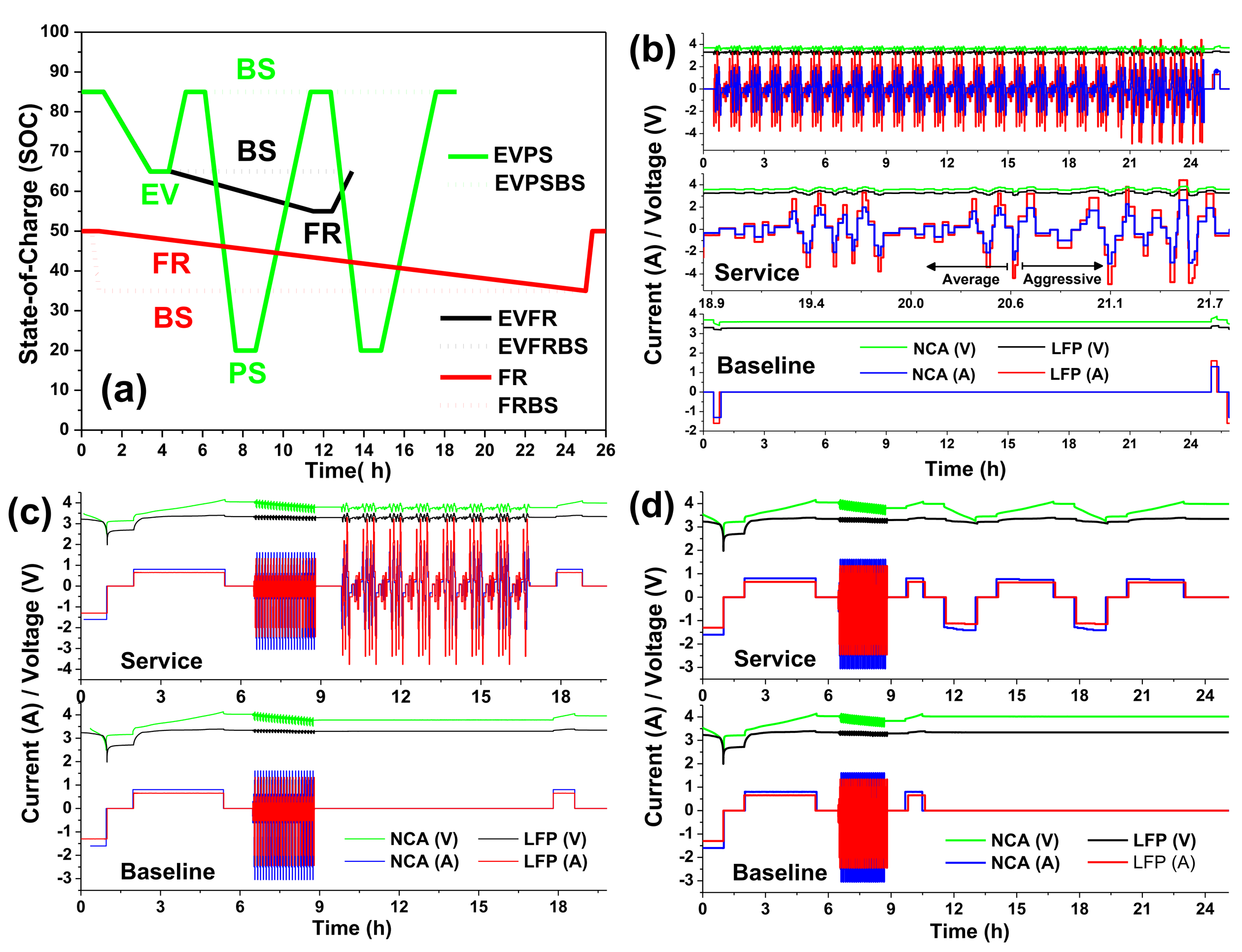

Figure 1. (a) State-of-charge (SOC) level versus time of various service and baseline (BS) cycles, (b) frequency regulation (FR) service (middle: expanded FR signal to highlight average and aggressive regimes), (c) electric vehicle and frequency regulation (EV-FR) scenario (FR is based on average regime), and (d) electric vehicle and peak-shaving (EV-PS) scenario.

Result & Discussion

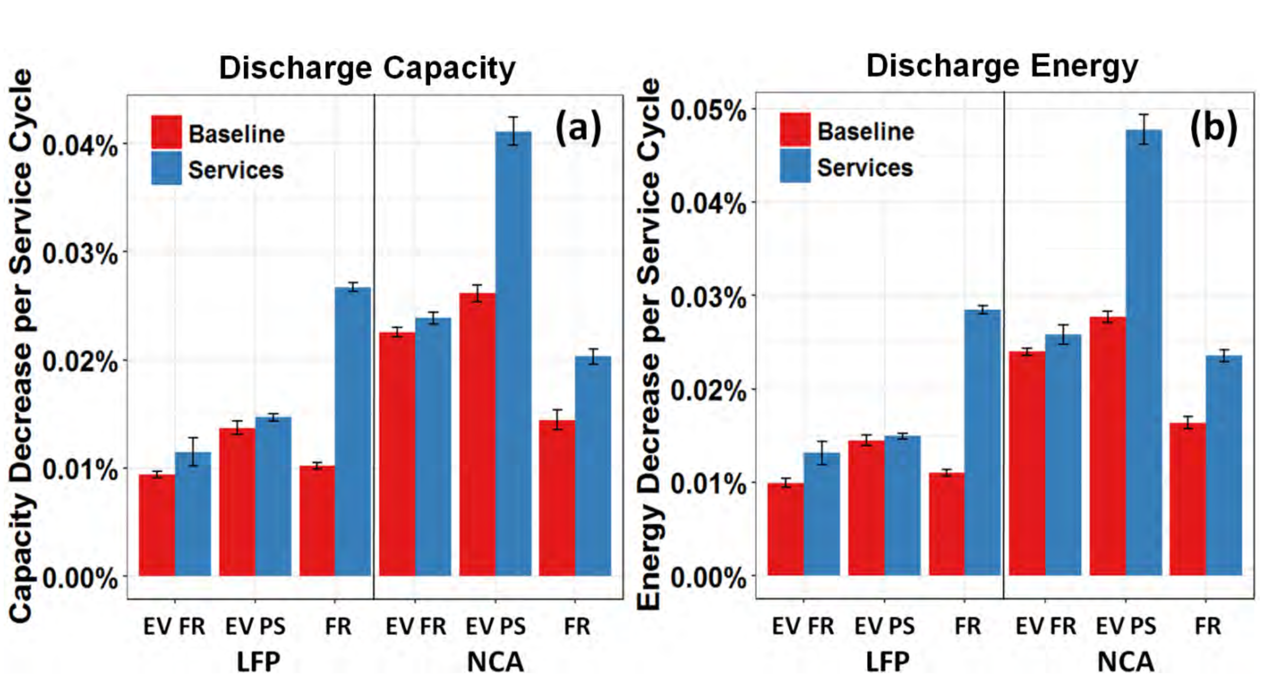

Figure 2. (a) Capacity and (b) energy degradation rate for frequency regulation (FR), electric vehicle-frequency regulation (EV-FR) and electric vehicle-peak shaving (EV-PS) scenarios.

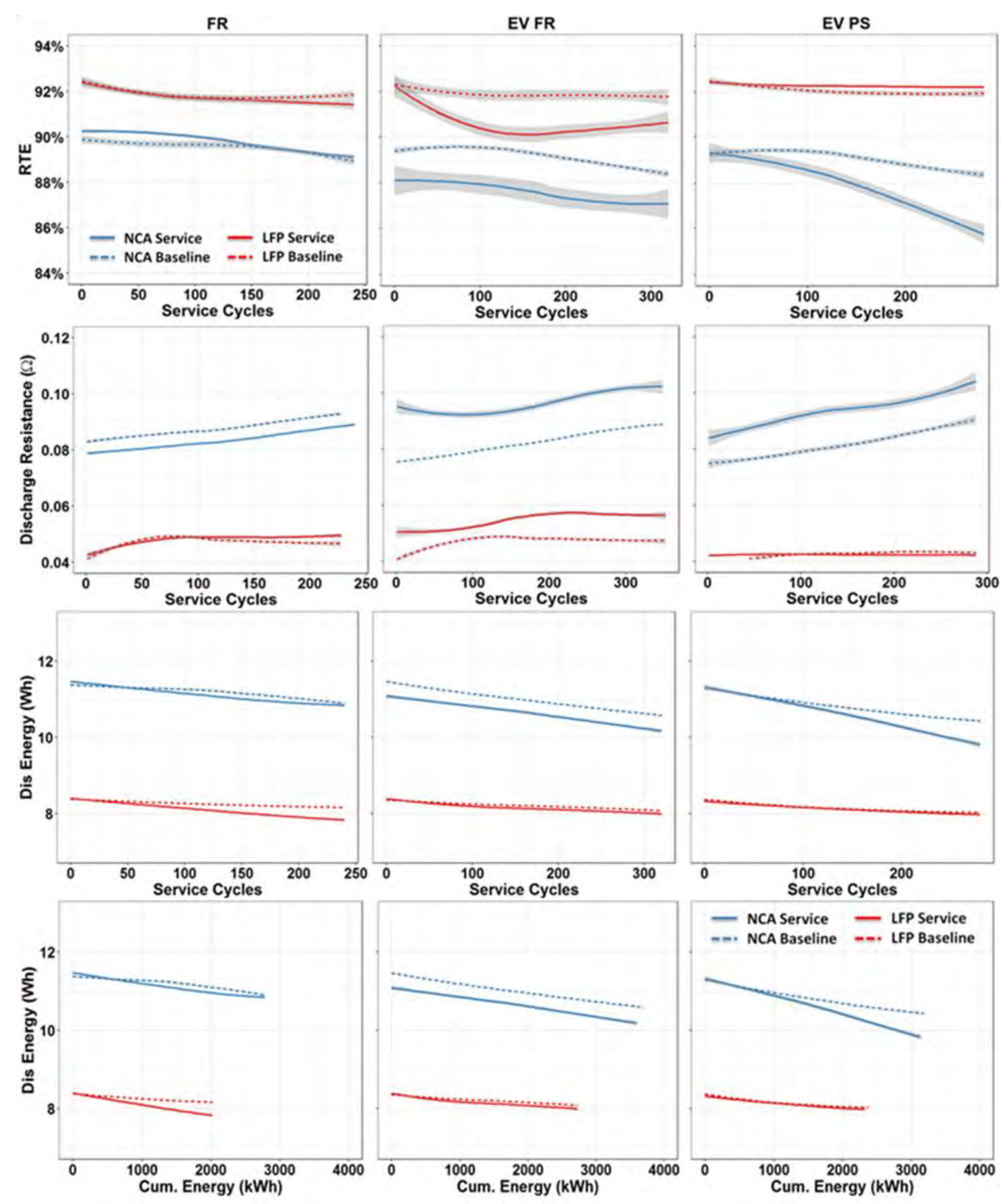

Figure 3. Round-trip efficiency (RTE), discharge resistance, and energy (vs. cycle and cumulative energy) of the NCA and LFP cells during the FR, EV-FR, and EV-PS scenarios. (: standard deviation of cells).

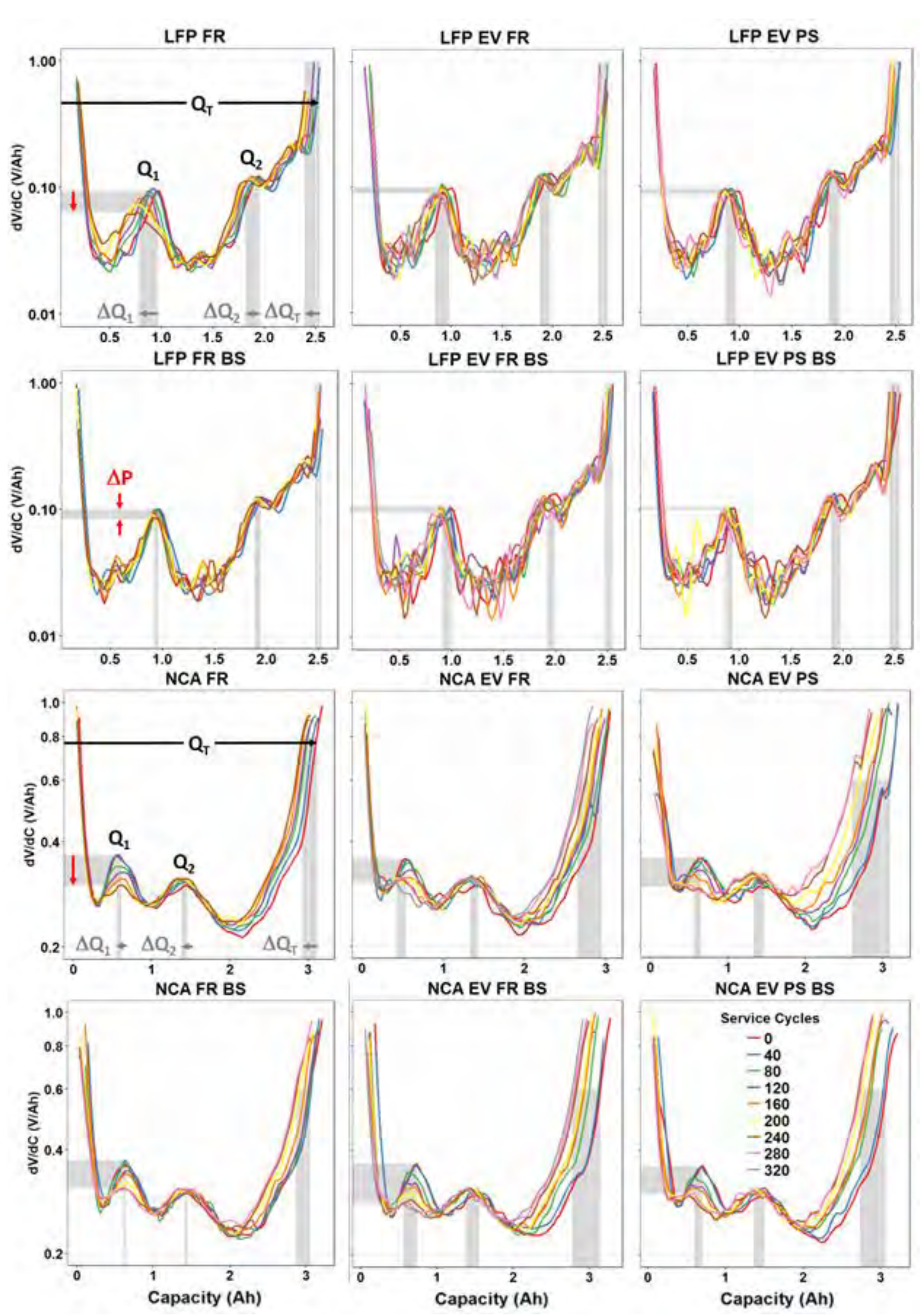

Figure 4. dV/dC (log scale) plot of NCA and LFP cells under various service and baseline cycles. (Q_1 & Q_2: characteristic graphite peaks, Q_T: total cell capacity, : changes from the initial state).

- dV/dC plot was obtained by averaging all cells under respective service applied.
- ΔQ : Changes in capacity.
- ΔP : Changes in peak height.

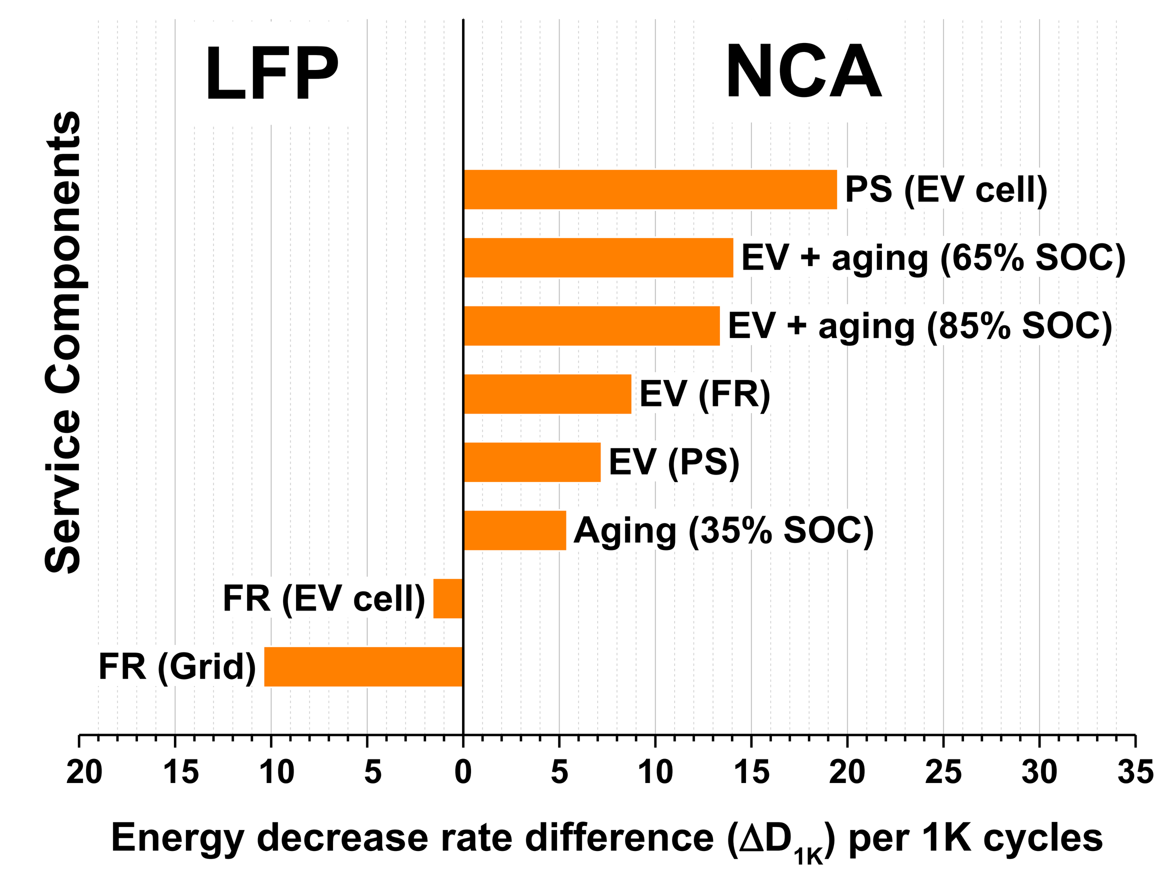

Figure 5. Energy decrease rate difference (ΔD_{1K}) in percentage per 1,000 cycles between LFP and NCA cell on service components.

- LFP cell utilize ~1.6 times more energy during FR service due to ~2 times higher C-rate applied.
- Higher degradation of LFP cell during FR (Grid) and FR (EV cell) might be due to 2 times higher C-rate applied.

Conclusion

1. LFP cells have better capacity, energy, and RTE retention for calendar aging, EV drive cycles, and PS grid service (high ΔSOC).
2. LFP and NCA EV cells have similar degradation rates for the FR grid service.
3. NCA cells have higher stability with respect to capacity and energy retention for FR grid services. The poorer performance of the LFP cells for high-power FR applications may be attributed to the higher C rates applied to compare with the NCA cells.
4. LFP cells have higher RTEs than NCA cells, irrespective of the service applied.
5. Cell resistance change trends varied between NCA and LFP cells. The NCA cells showed continuous increase, but the LFP cells displayed a parabolic increase with no significant change after 100 service cycles.
6. Understanding and mitigating the cathode chemistry-dependent resistance change due to SEI layer growth is critical for the longevity of the battery system during aging.

Acknowledgements

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2. S. F. DR Conover, A.J. Crawford, D.A. Schoenwald, J. Fuller, D.M. Rosewater, S.N. Gourisetti, V. Viswanathan, ***Protocol for Uniformly Measuring and Expressing the Performance of Energy Storage Systems***, Pacific Northwest National Laboratory and Sandia National Laboratories, 2016.

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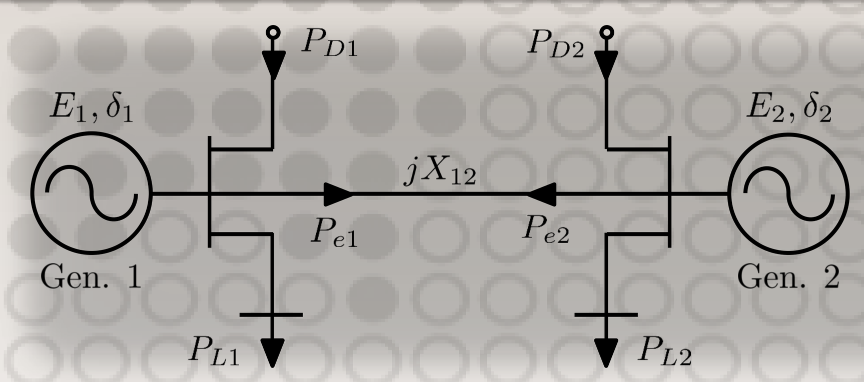
Control of Distributed Energy Storage Devices for Power Grid Resiliency

David Copp, Felipe Wilches-Bernal, Raymond Byrne, David Schoenwald

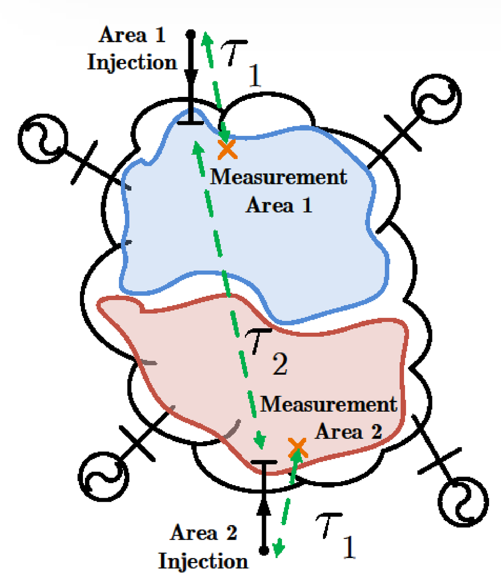
Damping control with feedback delays



Electromechanical model of generator dynamics

$\dot{\delta}_i = \Omega\omega_i$ Rotor angle

$2H_i\dot{\omega}_i = P_{mi} - P_{ei} - D_i\omega_i - \frac{1}{R_i}\omega_i - P_{Li} + P_{Di}$ Rotor angular velocity

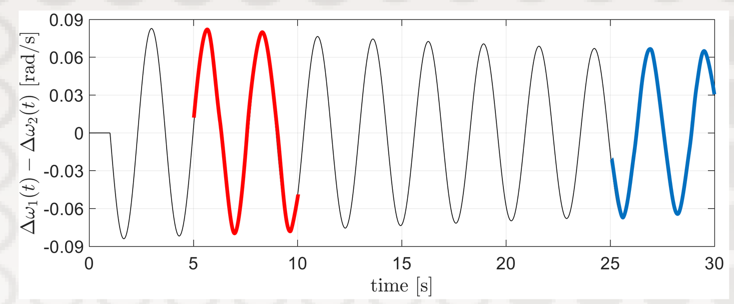


Delay Differential Equations

$$\dot{x}(t) = Ax(t) + A_1x(t-\tau_1) + A_2x(t-\tau_2)$$

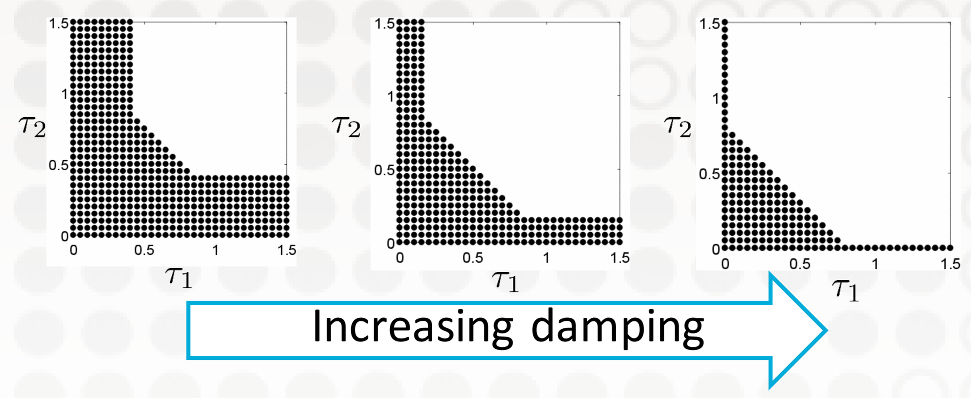
Stability Criterion

max |*red*| > max |*blue*| $\Longrightarrow$ stable



Energy Storage Power Injections

$$P_{D1}(t) = -k_d(\Delta\omega_1(t-\tau_1) - \Delta\omega_2(t-\tau_2))$$
$$P_{D2}(t) = k_d(\Delta\omega_1(t-\tau_2) - \Delta\omega_2(t-\tau_1))$$
$$\dot{x}(t) = Ax(t) + A_1^{\mathrm{ES}}x(t-\tau_1) + A_2^{\mathrm{ES}}x(t-\tau_2) + B_LP_L(t),$$

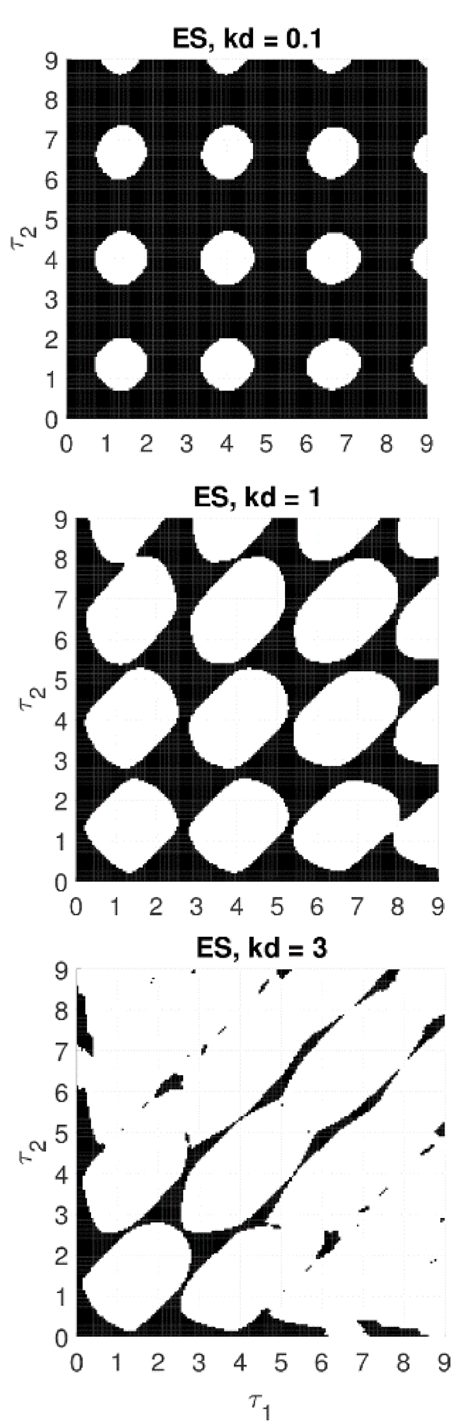


Lyapunov-Krasovskii Approach

General delay-dependent sufficient conditions for asymptotic stability (conservative) [1].

In the presence of delays, increasing damping may lead to instability.

Regions of Stability



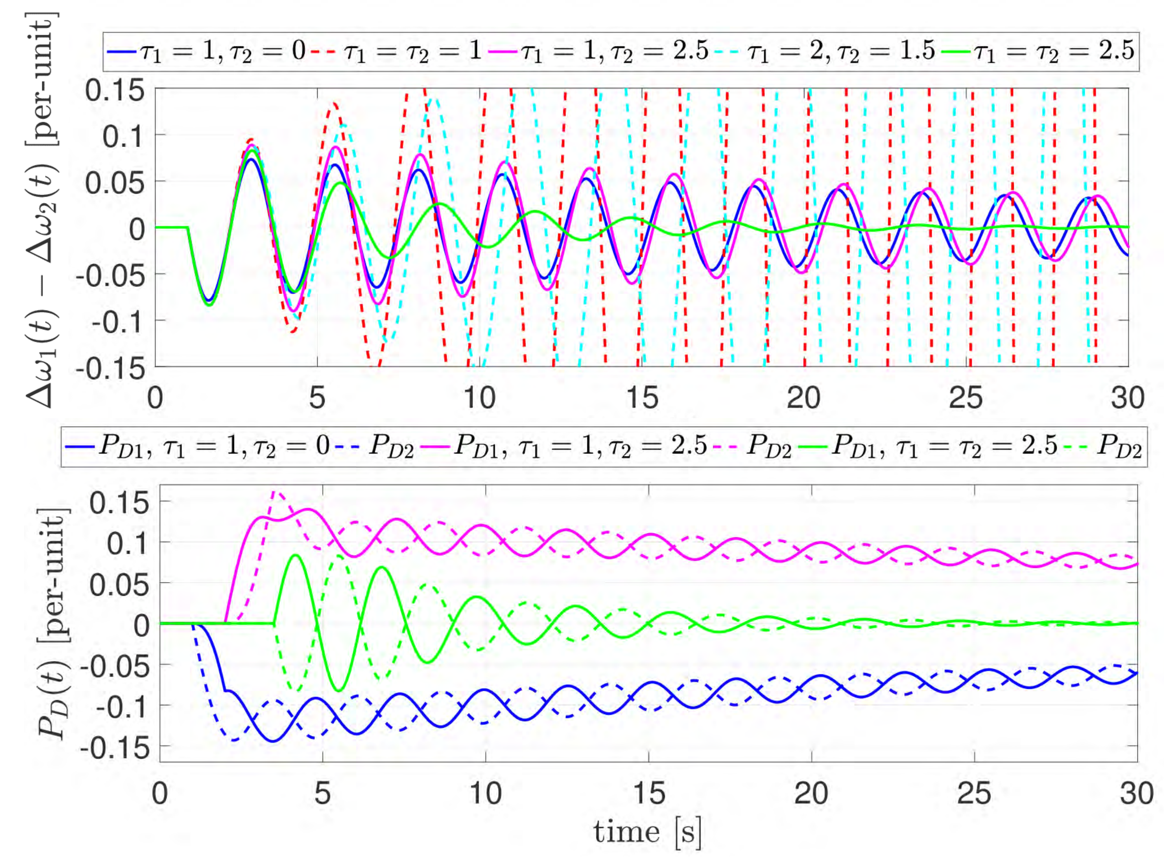
Time-Domain Simulations

Stable in black regions, unstable in white. Unstable regions grow as both gain and delays increase. Regions depend on frequency of oscillation and how close delays match that frequency. Measurement close to one period delayed may still be fairly accurate. Delayed measurement out-of-phase leads to incorrect feedback, and large gain will cause instability [2].

Period of oscillation ~2.73s

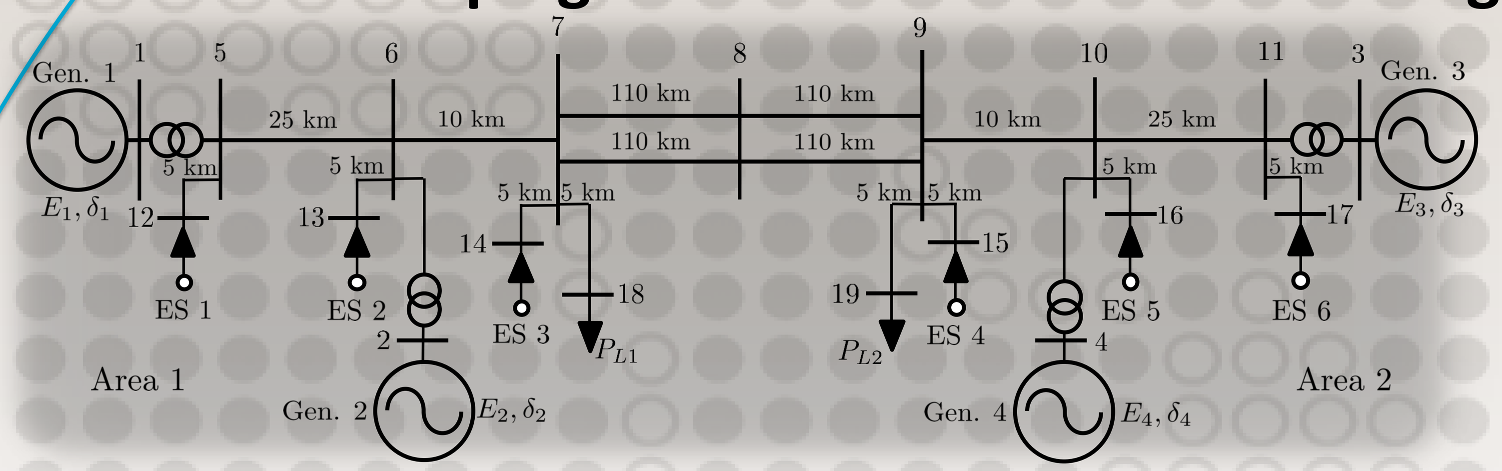
System oscillation (top)
Power injections (bottom)

When time delays are equal, injections are zero-mean. When time delays are asymmetric, injections are not zero-mean.



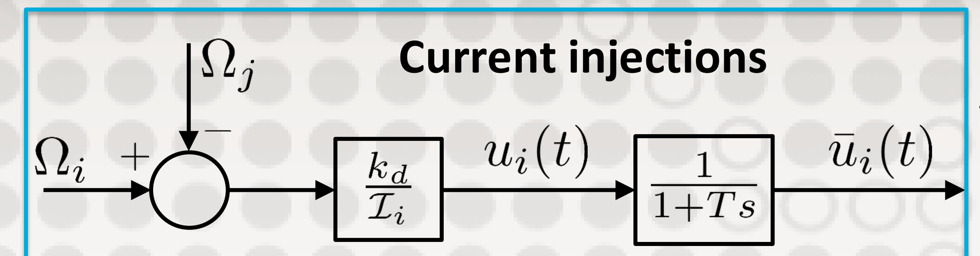
Power system stability via wide-area damping control

Damping control with distributed Energy Storage (ES)



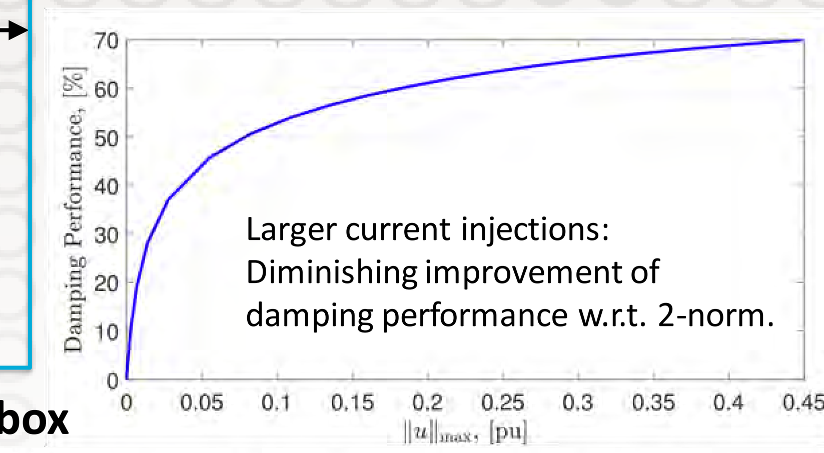
Two-area system: 4 generators, 6 ES devices.
Subtransient Generator Models (6^{th} order).
Ground bus fault at bus 7.

Current injections



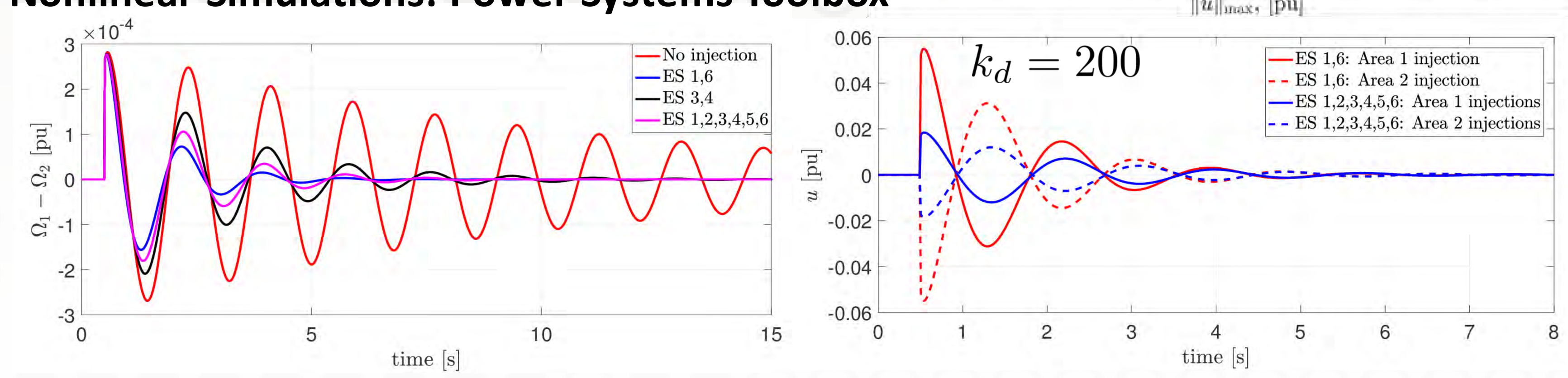
T ES response time
I_i # of injections
k_d Proportional gain
Ω_i Avg angular velocity of gens in area i

Which/how many ES devices should provide current injections to produce best damping of inter-area oscillations? [3]

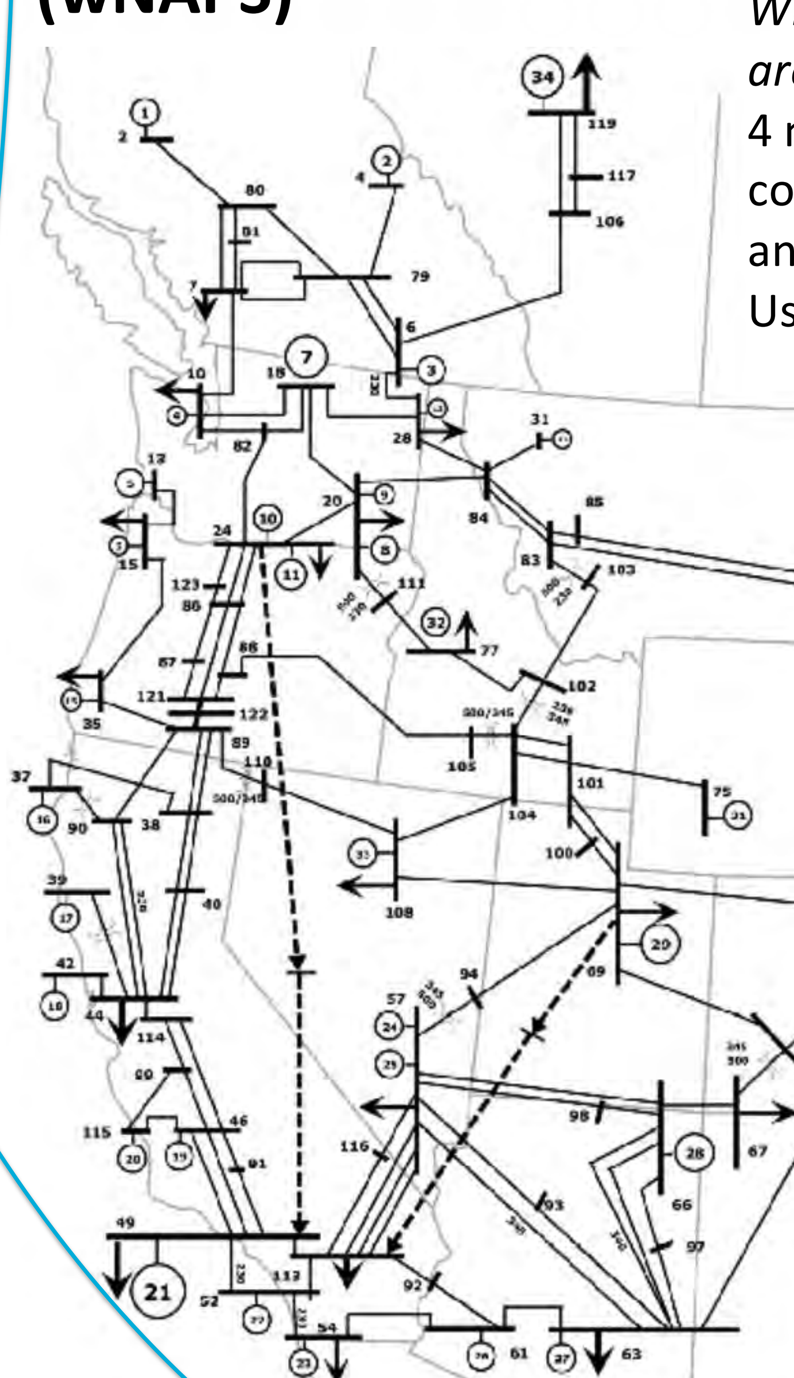


- Any injections are better than none. Figures show few combinations.
- Location is important. Injections near ends and in area with lower inertia produce better damping (not shown).
- Injections at all six locations perform almost as well as injections from only ES 1 and 6 with largest injection a third the size, allowing smaller (perhaps less expensive) ES devices to be installed.

Nonlinear Simulations: Power Systems Toolbox



Controllability and Observability in western North American Power System (wNAPS)



Where to place ES and measurement devices for best damping of inter-area oscillations?

4 modes of interest in the wNAPS. Use geometric measures of controllability/observability to determine where to inject power/current and where to collect measurements in linearized MiniWECC model [4]. Use this information to site and size storage.

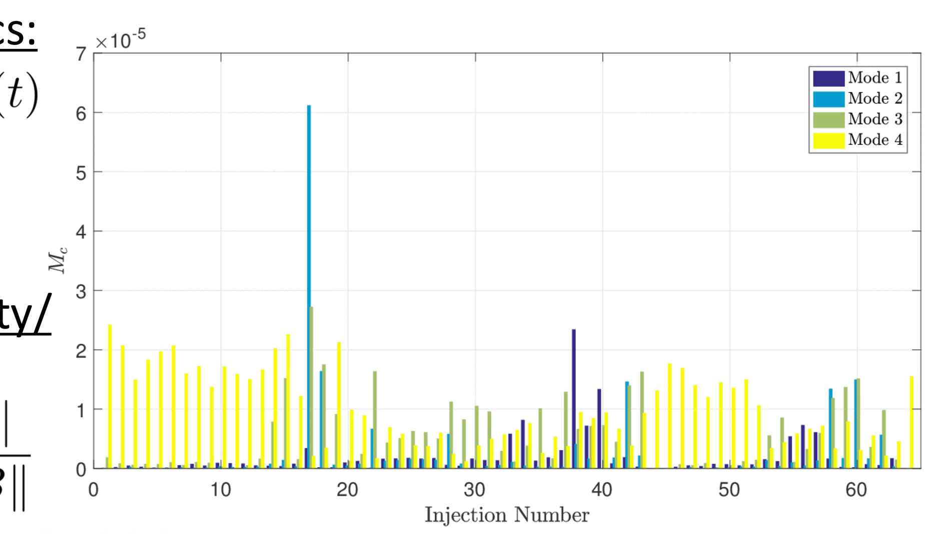
Linearized Dynamics:

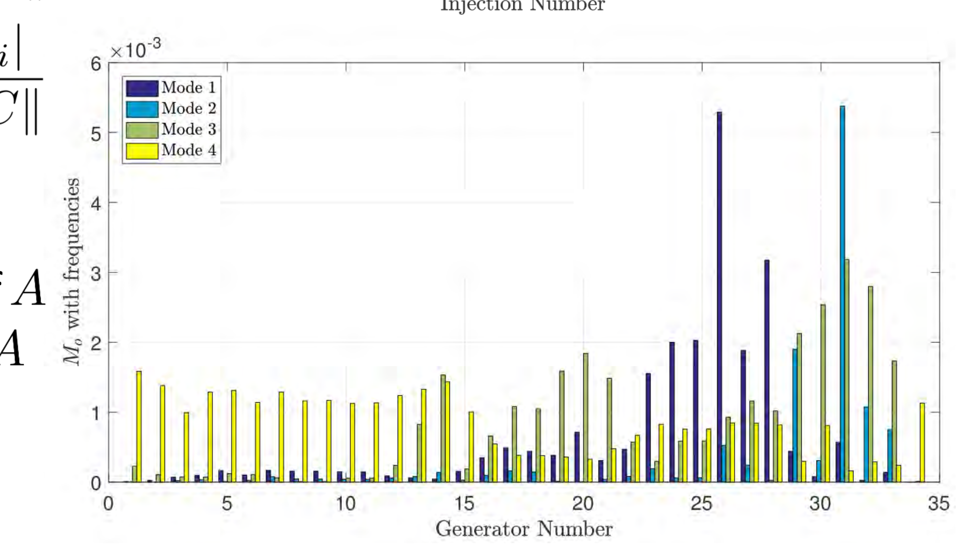
$$\dot{x}(t) = Ax(t) + Bu(t)$$
$$y(t) = Cx(t)$$

Measures of Controllability/ Observability:

$$Mc_i = \frac{|B^\top\psi_i|}{\|\psi_i\|\|B\|}$$
$$Mo_i = \frac{|C^\top\phi_i|}{\|\phi_i\|\|C\|}$$

ϕ_i right eigenvector of A
ψ_i left eigenvector of A





Other research topics: Optimal Energy Management with ES [5], Energy storage valuation

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[1] F. Wilches-Bernal, D.A. Copp, I. Gravagne, D.A. Schoenwald. Stability Criteria for Power Systems with Damping Control and Asymmetric Feedback Delays. *Submitted*, 2017.

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[3] D.A. Copp, F. Wilches-Bernal, D.A. Schoenwald. Power Systems Damping Control via Current Injections from Distributed Energy Storage. *10th Electrical Energy Storage Applications and Technologies Conference*, 2017.

[4] D. Trudnowski, "The MinniWECC System Model," Appendix 2 of J. Undrill and D. Trudnowski, "Oscillation Damping Controls," Year 1 report of BPA contract 37508, 2008.

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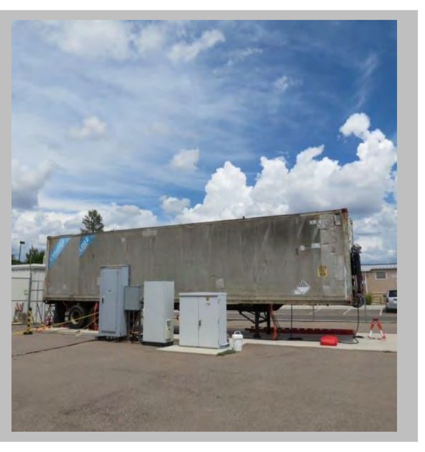

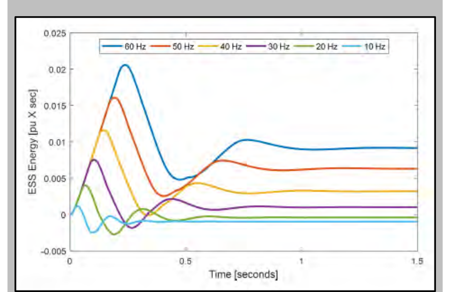

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Optimal Control of Energy Storage for Transient Stability

David Rosewater, Quan Nguyen, and Surya Santoso

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Q. Nguyen and S. Santoso are with the Department of Electrical and Computer Engineering University of Texas at Austin

Power system stabilizers (PSS) are employed to enhance the transient stability of power systems by providing rapid damping for oscillations of generator rotor angle and speed. Where a PSS is insufficient, energy storage systems (ESS) can provide more damping to the system. Figure 1 shows a single machine infinite bus (SMIB) model with both PSS and ESS implemented. Figure 2 shows the control flow block diagram for this systems.

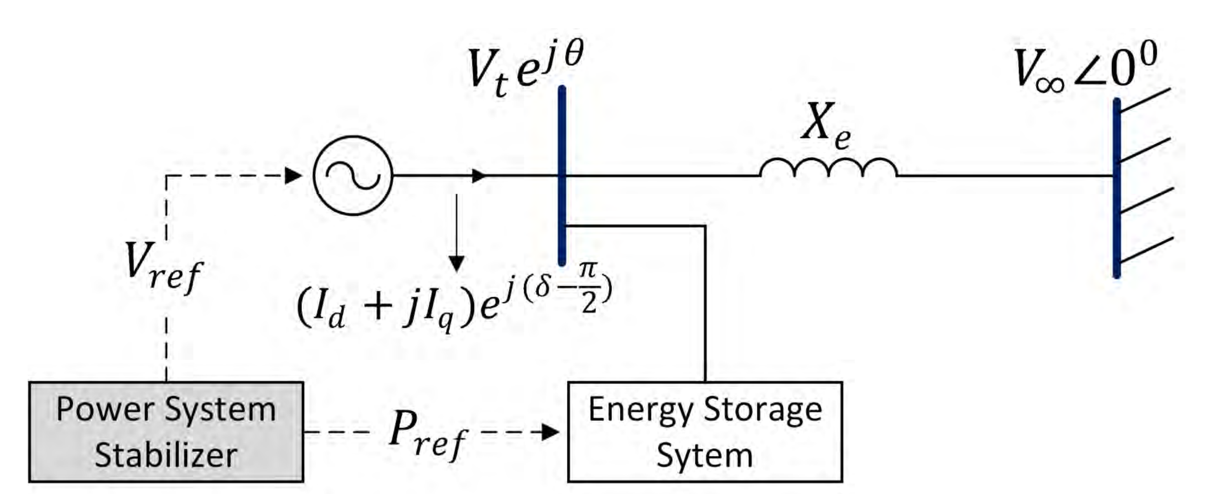

Figure 1 Single Machine Infinite Bus Model

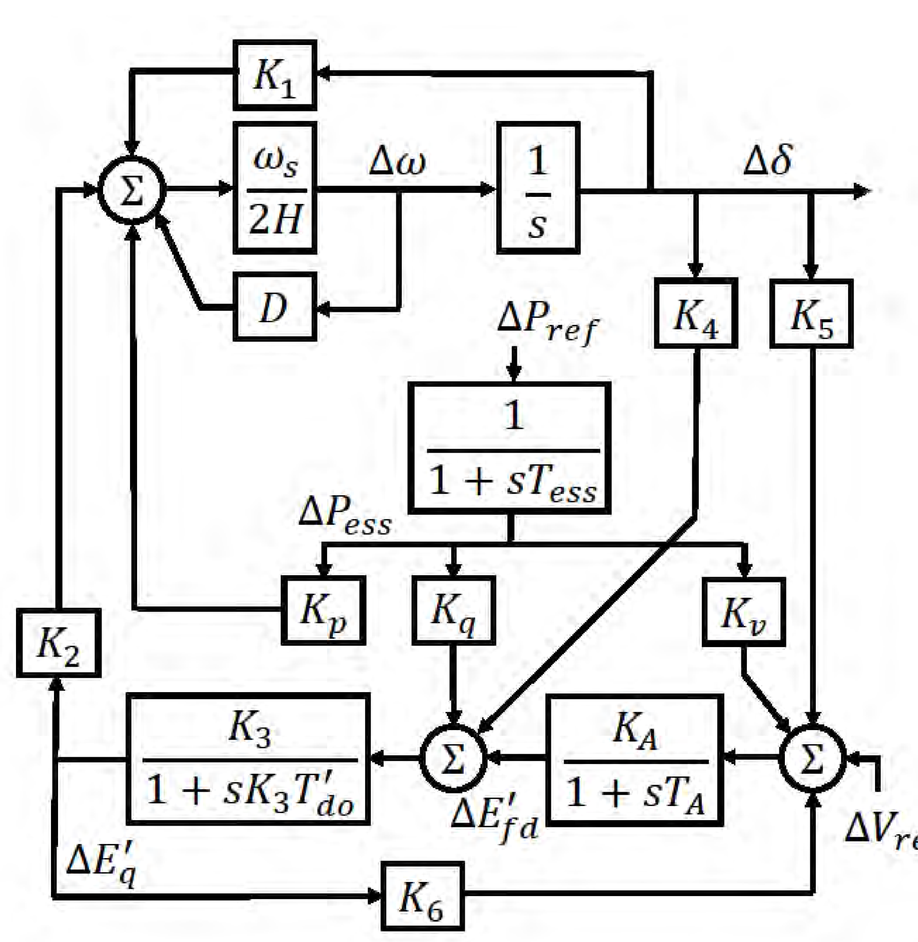

Figure 2 Control Flow Block Diagram

State feedback is calculated to optimize a performance objective function (L). The objective, shown below, is chosen to be a linear combination of the squared frequency and angle disturbances.

$$L = \frac{1}{2}\int_0^\infty \left[(\Delta\delta)^2 + (\Delta\omega)^2 + r_1(\Delta V_{ref})^2 + r_2(\Delta P_{ref})^2\right] dt$$

$$\mathbf{u}^* = [\Delta V_{ref}\ \Delta P_{ref}]^T \qquad \mathbf{u}^* = -\mathbf{K}\mathbf{x}, \mathbf{K} = \mathbf{R}^{-1}\mathbf{B}^T\mathbf{S}^*$$

In a test system, the rotor speed is assumed to have an initial disturbance of 0.12 Hz. The open-loop system is nearly unstable at 60 Hz with a settling time of 63.37 seconds.

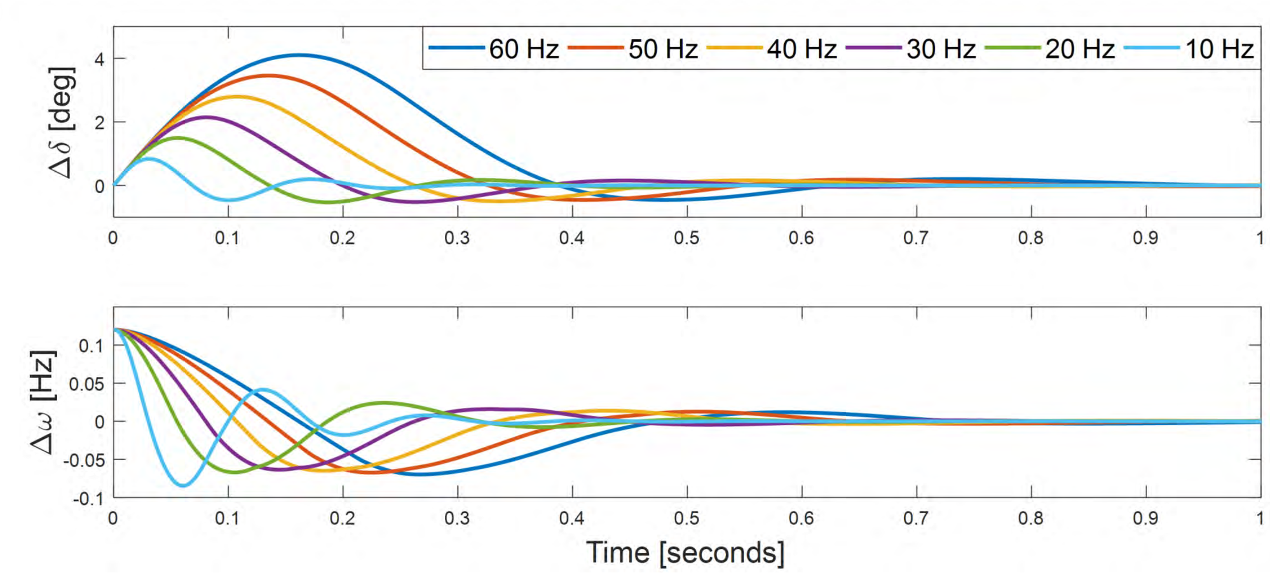

Figure 3 State Damping ver. Frequency

The impact of the ESS is studied by varying the coefficient r_2. As shown in Table I, without the ESS ($r_2 = \infty$) the controller is able to reduce settling time to 7.5 seconds and 4.8 seconds, at 60 Hz and 50 Hz respectively. With ESS, the designed PSS reduces the settling time to 1.14 seconds and 1.07 seconds at 60 Hz and 50 Hz, respectively. Based on the slight improvement of the result at 50 Hz over 60 Hz, the complete state responses and settling times when the operating frequency is further reduced are shown in Fig. 3 and Table II.

TABLE I
SETTLING TIME PERFORMANCE WITH/WITHOUT ESS

	60 Hz		50 Hz	
State	$r_2 = 0.05$	$r_2 = \infty$	$r_2 = 0.05$	$r_2 = \infty$
$P_{ess(p.u.\times sec.)}$	0.2008	0	0.1925	0
$E_{ess(p.u.\times sec.)}$	0.0202	0	0.0152	0
$\Delta\delta(sec.)$	1.1436	7.3812	1.0206	4.7187
$\Delta\omega(sec.)$	0.9994	7.5007	1.0655	4.8119

TABLE II
SETTLING TIME PERFORMANCE AT DIFFERENT OPERATING FREQUENCIES

State	60 Hz	50 Hz	40 Hz	30 Hz	20 Hz	10 Hz
$P_{ess(p.u.\times sec.)}$	0.2008	0.1925	0.1857	0.1795	0.1671	0.1658
$E_{ess(p.u.\times sec.)}$	0.0202	0.0152	0.0106	0.0067	0.0037	0.0021
$\Delta\delta(sec.)$	1.1436	1.0206	0.8778	0.8580	0.7593	0.7382
$\Delta\omega(sec.)$	0.9994	1.0655	0.9285	0.7665	0.6853	0.6376

The stability improvements achieved by conventional power system stabilizers (PSS), energy storage system (ESS) damping, and low-frequency high-voltage alternating current (LF-HVac) transmission are stackable. For an example system at 60 Hz, the classical PSS design improves settling time from 63.37 seconds to 7.5 seconds. Employing ESS further reduces the settling time to 1.14 seconds and reducing the operating frequency to 10 Hz improves it to 0.74 seconds.

This work was funded in part by the U.S. DOE OE's energy storage program.

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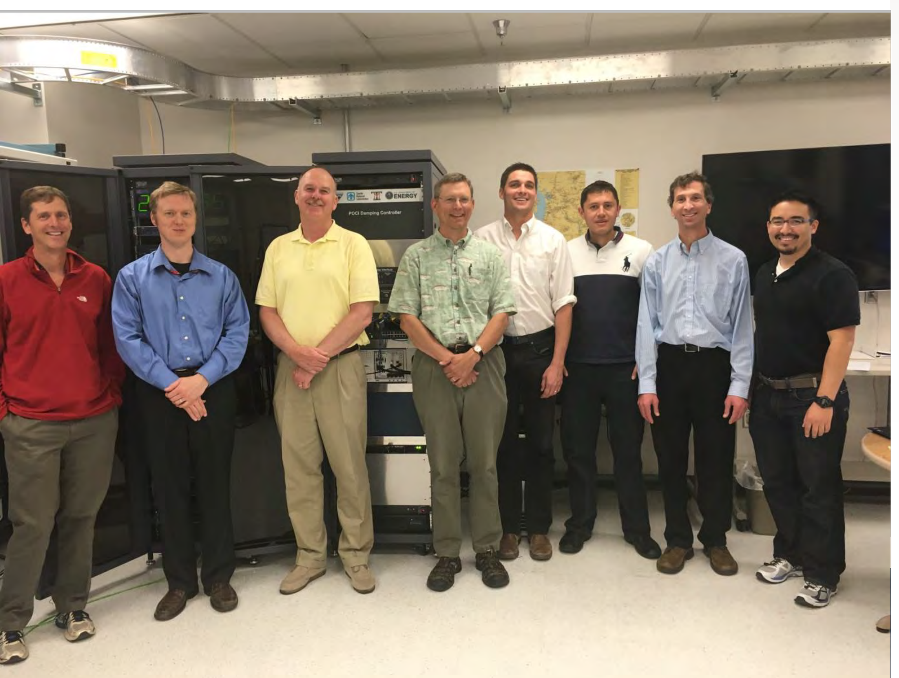

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BPA Damping Control Project

Dave Schoenwald, Sandia National Labs

The project team gratefully acknowledges the support of the DOE-OE Energy Storage Program managed by Dr. Imre Gyuk, the DOE-OE Transmission Reliability Program managed by Mr. Phil Overholt, and the BPA Office of Technology Innovation, TIP # 289, PM: Dr. Jisun Kim, Technical POC: Dr. Dmitry Kosterev.

Project Overview

Problem:

- **Poorly damped inter-area oscillations jeopardize grid stability and can lead to widespread outages during stressed grid conditions**
- **Oscillation stability limits constrain power flows well below transmission capacity: Inefficient use of expensive infrastructure investments**

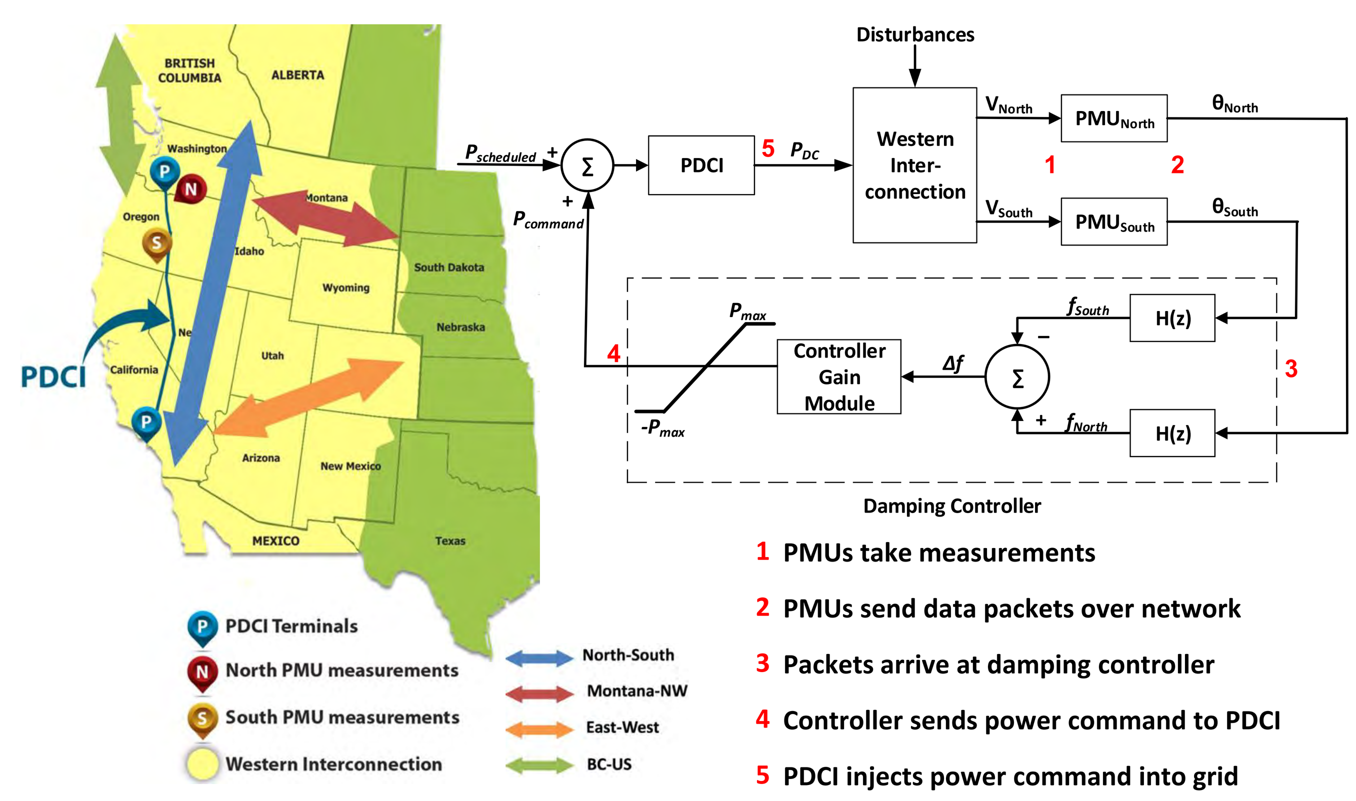
Solution:

- **Construct closed-loop feedback signal using real-time PMU data: 1st demonstration of this in North America**
- **Modulate power flow on PDCI (up to +/- 125 MW) ➔ targets troublesome North-South modes**
- **Implement a supervisory system to ensure "Do No Harm" to grid and monitor damping effectiveness**

Benefits:

- **Improved reliability for stressed grid conditions**
- **Avoided costs from a system-wide blackout (>> $1B)**
- **Reduced or postponed need for new transmission capacity: $1M–$10M/mile**
- **Helps meet growing demand by enabling higher power flows on congested corridors**

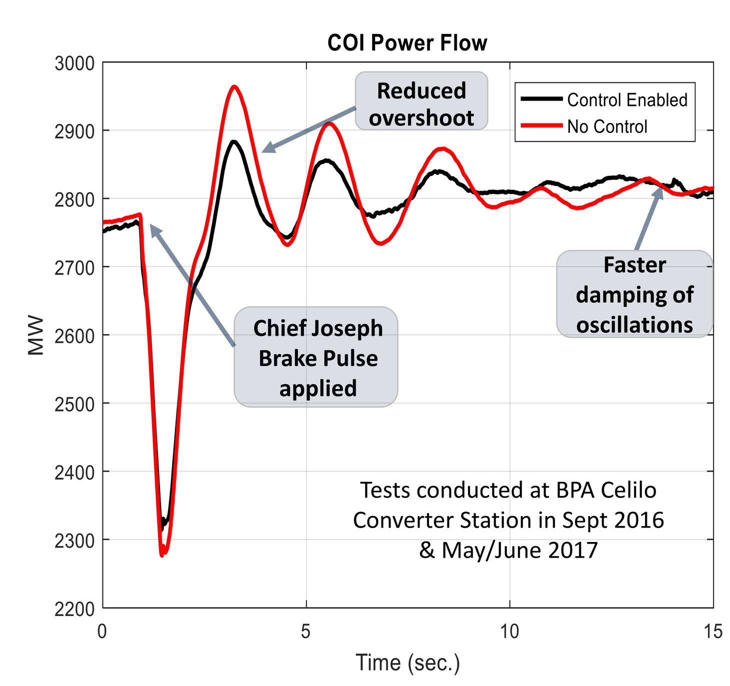
Damping Controller Strategy



Key Takeaways from Project that will Benefit the Design of Control Systems Deploying Energy Storage

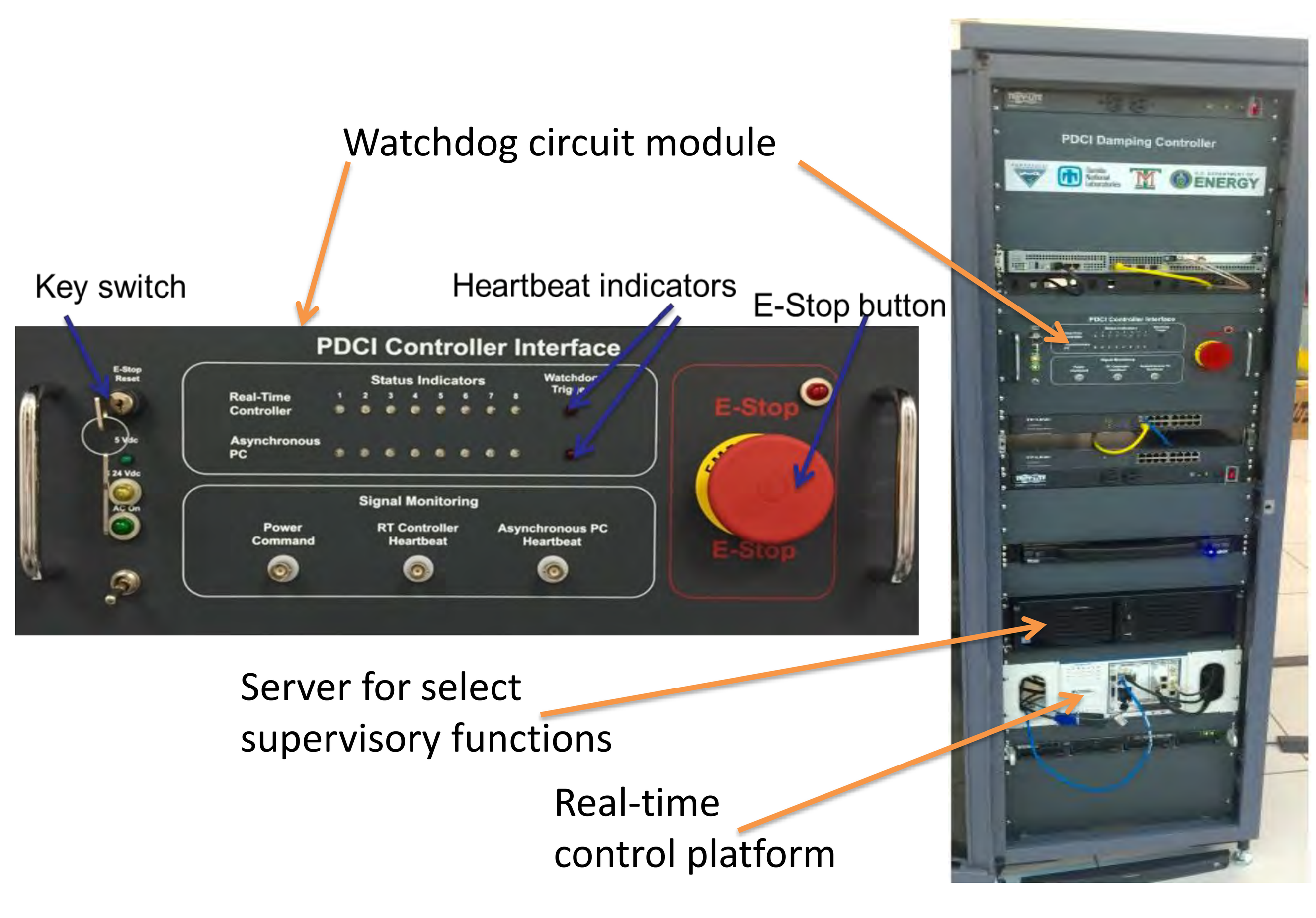
- Expertise gained in implementing real-time network-based PMU data for feedback control is directly applicable to controller design using distributed energy storage.
- Supervisory system architecture can be incorporated into the design of failsafe control systems using energy storage.

Controller Tests on the PDCI have Consistently Demonstrated Significant Improvements in Damping

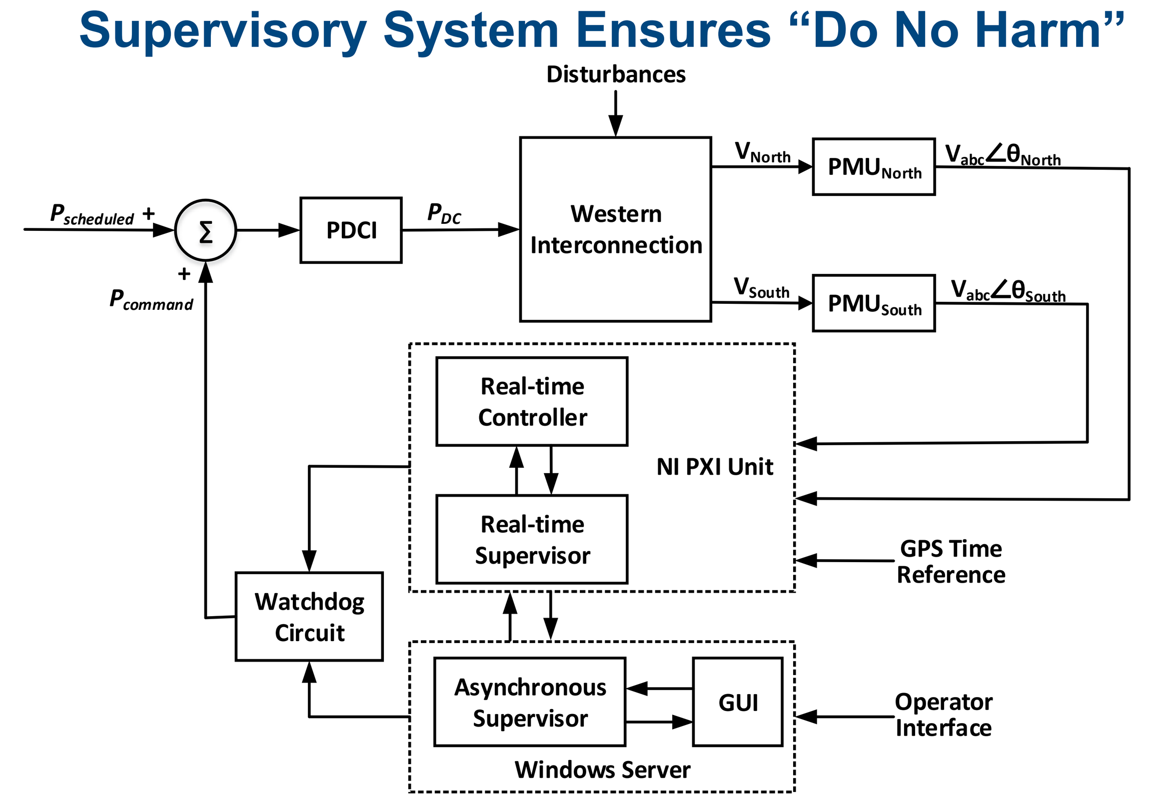


- Feedback control using phasor measurement unit (PMU) data: **First tests in North America** successfully demonstrating real-time PMU feedback control on a large-scale power grid.
- Controller modulates power flow on Pacific DC Intertie (PDCI) by up to +/- 125 MW
- Controller incorporates a supervisory system to ensure **"Do No Harm"** to power grid
- Primary controller benefits:
  1. **Improved system reliability**
  2. **Higher power transfer limits**

Damping Controller Hardware



Supervisory System Ensures "Do No Harm"



Watchdog Circuit: Detects hardware failures, ensures smooth state transitions, handles E-stop functions.

Real-time Supervisor: Monitors latencies and data quality, switching to other PMU sites if needed.

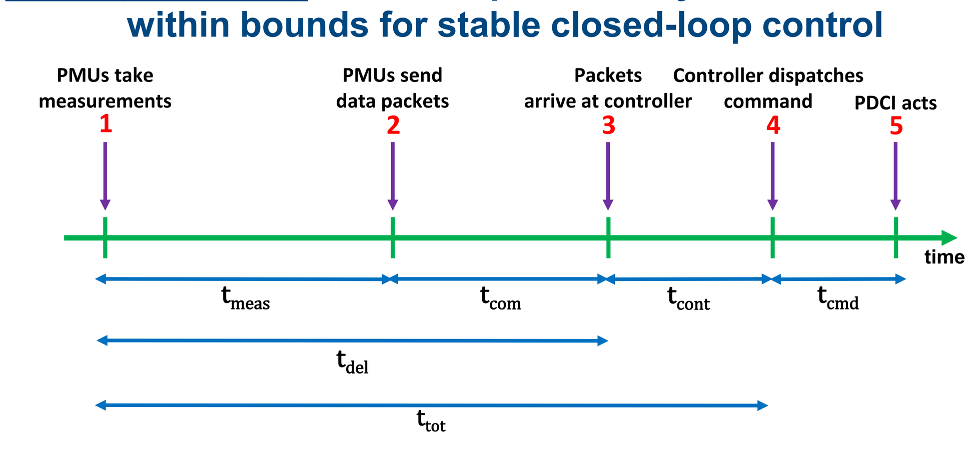
Asynchronous Supervisor: Estimates gain/phase margin, PDCI health, slower-than-real-time tasks.

Summary of Project Accomplishments

- **First successful demonstration of wide-area control using real-time PMU feedback in North America ➔ Design expertise in using PMUs for control can be leveraged for other applications, including control design for energy storage systems.**
- **Control system design is very tolerant to network-induced time delays from feedback of real-time PMU measurements.**
- **Experience gained in networked controls will advance distributed control of networked assets including distributed energy storage.**
- **Supervisory system architecture and design can be applied to future real-time grid control systems to ensure "Do No Harm".**
- **Extensive eigensystem analysis and visualization tools developed for simulation studies and analysis of test results.**
- **Model development and validation for multiple levels of fidelity to support analysis, design, and simulation studies.**

Time Delays in PDCI Damping Control

Primary takeaway: Round trip time delays < 100 ms ➔ well within bounds for stable closed-loop control



Symbol	Name	Mean	Range	Distribution
t_{meas}	PMU Delay	50 ms	Assumed fixed at 50 ms	N. A.
t_{com}	Communications Delay	10 ms	[5,38]	Heavy Tail Normal
t_{del}	Signal Delay	60 ms	[55,88]	Heavy Tail Normal
t_{cont}	Control Processing Delay	11 ms	[3,17]	Bimodal Normal with peaks at 8 & 15 ms
t_{tot}	Total Controller Delay	71 ms	[58,102]	Bimodal Normal with peaks at 66 & 73 ms
t_{cmd}	Command Delay	Estimated at 11 ms	Assumed fixed at 11 ms	N. A.
t_{eff}	Effective Delay	82 ms	[69,113]	Bimodal Normal with peaks at 77 & 84 ms

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Optimal Control for Battery Storage Using Nonlinear Models

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ABSTRACT

Successful assessment and deployment of a battery storage system (BSS) require optimizing its operation and therefore maximizing the potential benefits. In existing studies on economic assessment and optimal scheduling of BSS, fixed energy and power rating, and constant efficiencies are assumed, which could lead to inaccurate assessment results and even infeasible operation schedules. We propose a nonlinear battery model and an optimal scheduling method to better capture varying power and energy rating as well as efficiencies. Dynamic programing based algorithm is developed to solve the nonconvex optimal scheduling problem. The proposed method is compared with a representative linear optimization method based on simplified BSS model through a real-world energy storage evaluation project to show the significance of the proposed method.

EXISTING METHODS

Optimal scheduling with simplified linear BSS model:

$$\mathbf{P}_1: \max_{p_k, p_k^{\text{batt}}, s_k, \Delta s_k} \sum_{k=1}^{K} \lambda_k p_k$$

subject to:

$$\begin{aligned}
&\text{Charging/discharging limit:} && -p^-_{\max} \le p_k \le p^+_{\max}, && \forall k = 1, \cdots, K\\
&\text{Rate change of energy in batt.:} && p_k^{\text{batt}} = \begin{cases} p_k/\eta^+ & \text{if } p_k \ge 0 \\ p_k \eta^- & \text{if } p_k < 0 \end{cases}, && \forall k = 1, \cdots, K\\
&\text{SOC change:} && \Delta s_k = p_k^{\text{batt}} \Delta T / E_{\max}, && \forall k = 1, \cdots, K\\
&\text{Dynamics of SOC:} && s_k = s_{k-1} - \Delta s_k, && \forall k = 1, \cdots, K\\
&\text{SOC limits:} && \underline{S}_k \le s_k \le \overline{S}_k, && \forall k = 1, \cdots, K
\end{aligned}$$

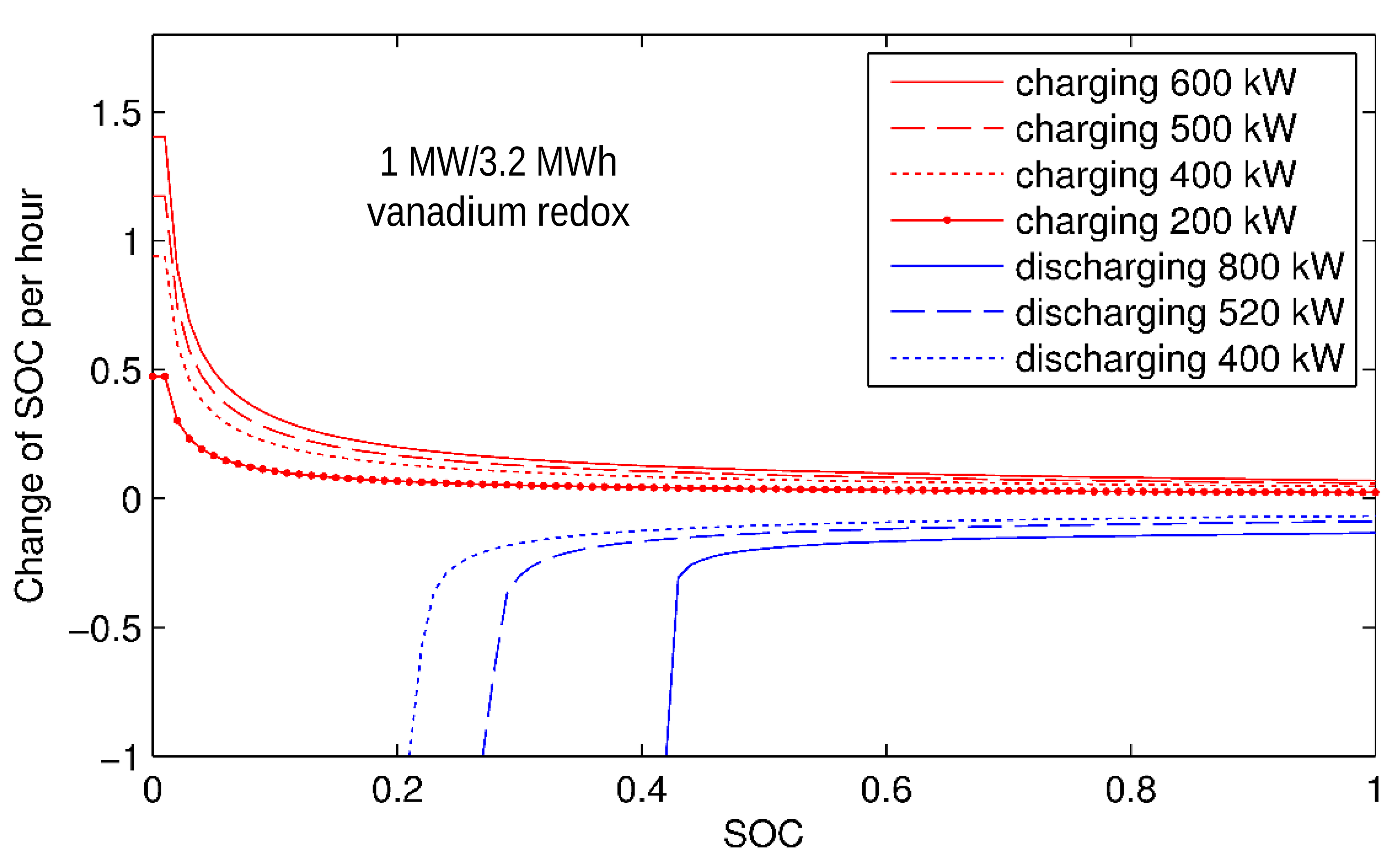
Limitations:

$[-p_{\min}, p_{\max}]$: incapable to model varying charging/discharging range

$E_{\max}$: inaccurate to represent energy capacity

η^-, η^+: inaccurate to represent energy capacity

BSS MEASURED DATA



PROPOSED METHOD

Optimal scheduling with nonlinear BSS model:

$$\mathbf{P}_2: \max_{p_k, s_k, \Delta s_k} \sum_{k=1}^{K} \lambda_k p_k$$

subject to:

$$\begin{aligned}
&\text{Charging/discharging limit:} && p_k \in \mathcal{P}_{s_k}, && \forall k = 1, \cdots, K\\
&\text{SOC change:} && \Delta s_k = f(p_k, s_k), && \forall k = 1, \cdots, K\\
&\text{Dynamics of SOC:} && s_k = s_{k-1} - \Delta s_k, && \forall k = 1, \cdots, K\\
&\text{SOC limits:} && \underline{S}_k \le s_k \le \overline{S}_k, && \forall k = 1, \cdots, K
\end{aligned}$$

p : charging/discharging power

$\mathcal{P}_s$: feasible set of power for a SOC level s

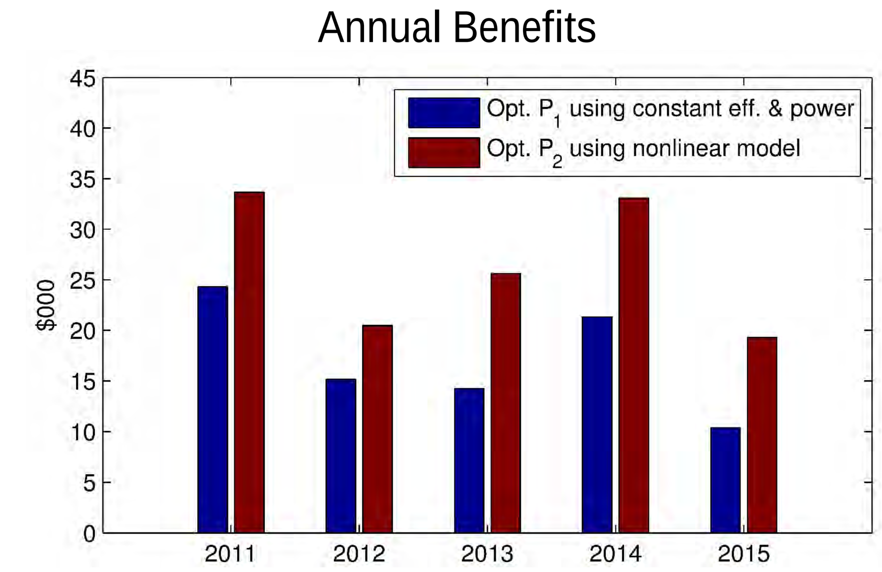
s: SOC level

Δs: SOC change rate

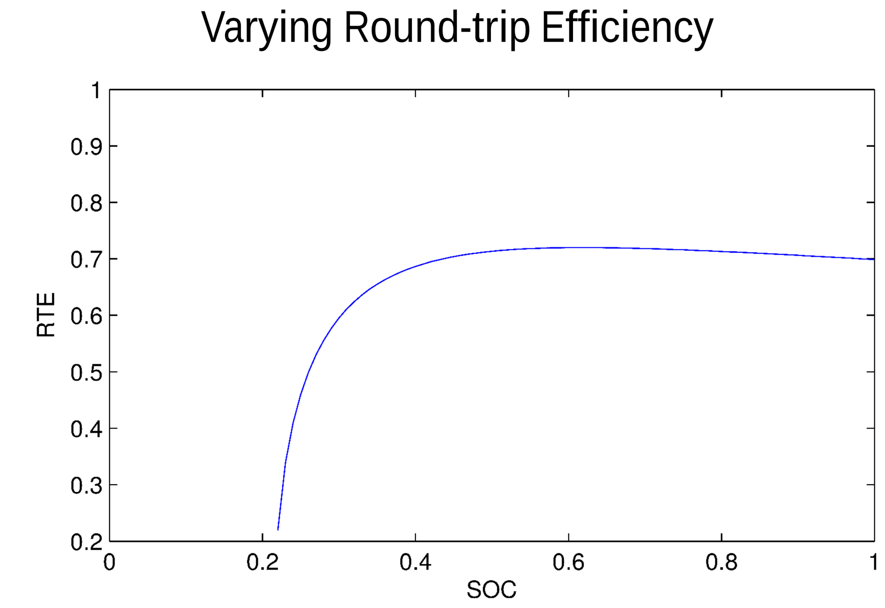
CASE STUDY

2 MW/6.4 MWh vanadium redox for energy arbitrage

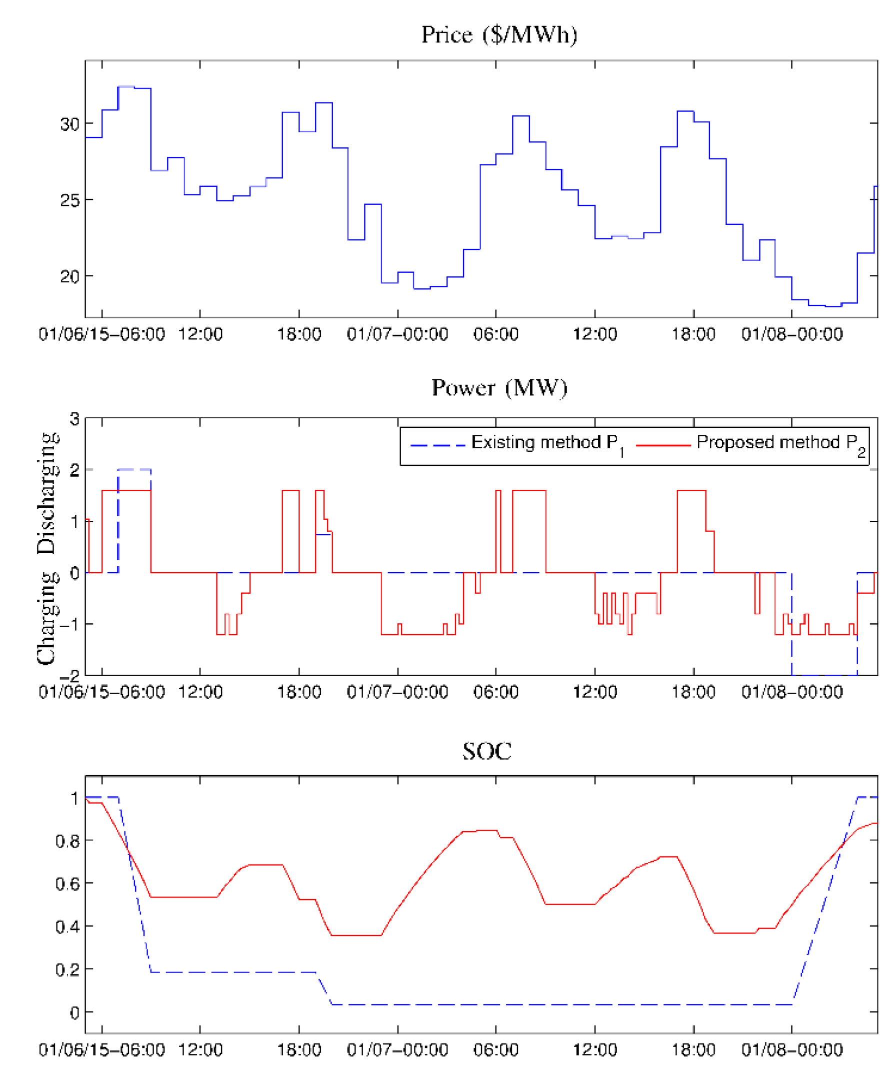
Annual Benefits



Varying Round-trip Efficiency



Power and SOC on Sample Days



CONCLUSIONS AND FUTURE WORK

- Nonlinear BSS model better captures varying charging/discharging power capacity and efficiencies.
- Optimal scheduling using simplified linear BSS model could lead to significant errors in benefit assessment , and even infeasible operating schedule.
- Optimal scheduling and economic assessment using the proposed nonlinear model will be developed for other grid and/or customer-side applications.

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Determining the internal pressure in 18650 format lithium ion batteries under thermal abuse

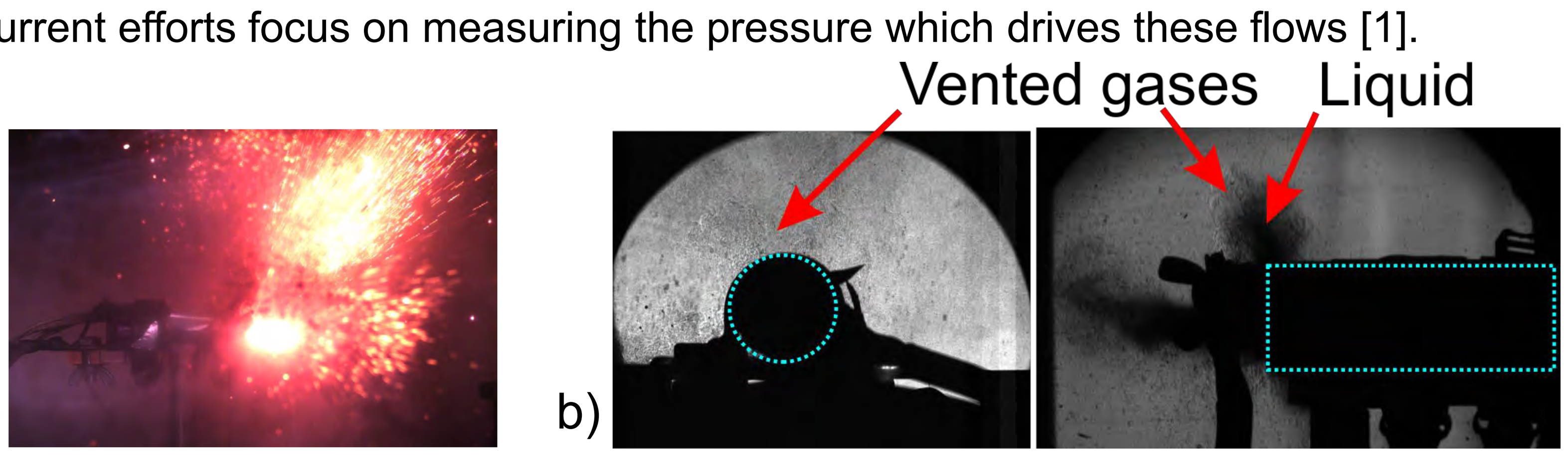
Frank Austin Mier[a], Michael J. Hargather[a], Summer R. Ferreira[b]
(a) Mechanical Engineering Dept., New Mexico Tech, (b) Sandia National Laboratories

Abstract

Lithium batteries have a well-known tendency to fail violently under abuse conditions which can result in venting of flammable material. Understanding these events can aid in evaluating safety associated with individual battery cells and battery packs when these fluids are vented. The external fluid dynamics of the venting process, including liquid droplets and gases, is directly related to the internal pressure of the battery cell. In this work, battery case strain is measured on cells under thermal abuse which is then used to calculate the internal pressure via hoop and longitudinal stress relations. Strain measurement is a non-invasive approach which will have no bearing on the decomposition within batteries that leads to thermal runaway. Complementary tests are performed to confirm the strain-pressure relationship by pressurizing 18650 cell caps to failure with an inert fluid. A laboratory setup with a heated test chamber was designed and fabricated to remotely subject cells to heating rates up to 6 ˚C/min. Additional measurements include cell temperature and the test chamber pressure, temperature, and heat flux. Variables explored in these tests include cell chemistry, state of charge, and heating rate.

Battery venting under abuse conditions

Most commercial batteries have a vent to relieve pressure as gases are generated under abuse conditions. Shown in Figure 1(a), these events can be highly energetic, and quantitatively describing these events can aid in understanding risks and aid in smart design. Previous work at New Mexico Tech has focused on high-speed schlieren imaging the gas and liquid flows from lithium ion batteries under various abuse conditions as shown in Figure 1(b) while current efforts focus on measuring the pressure which drives these flows [1].

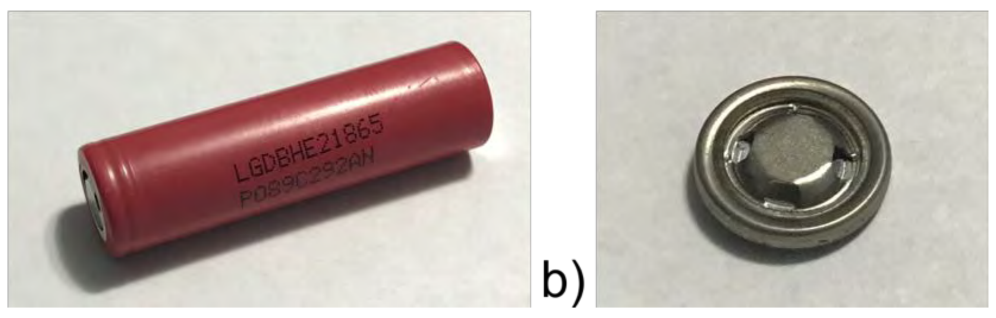


a) b)

Figure 1: (a) An 18650 cell venting during abuse testing which lead to combustion of expelled material. (b) Schlieren images of a different test from end and side views.

Direct pressurization of battery vent caps

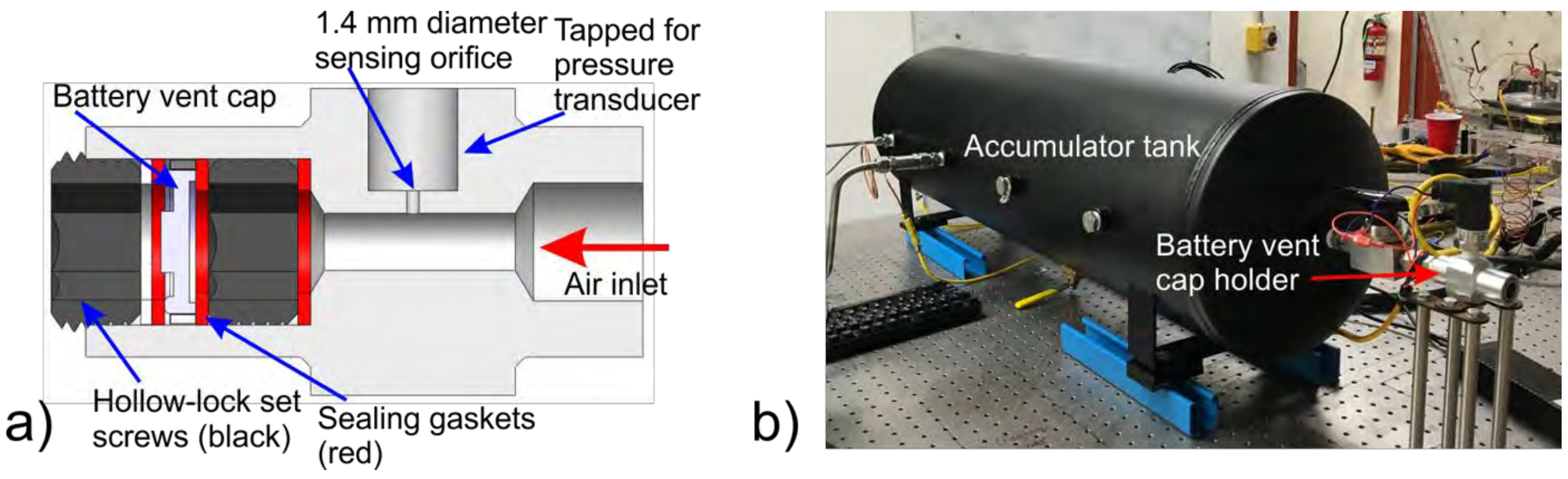
An apparatus has been designed and constructed to accurately measure the burst pressure of battery vents under pressurization with dry air to best describe how venting will occur and to support the battery case strain tests. Typical 18650 construction includes a vent mechanism that is crimped in place as part of the positive terminal of a cell. The vents tested here are removed from actual cells, and the entire vent mechanism remains intact as seen in Figure 2.



a) b)

Figure 2: (a) An intact 18650 format battery (LG HE2) and (b) the vent cap after removal.

Shown in Figure 3, major components included in this setup are the battery vent cap holder, accumulator tank, pressure regulator, and compressed air cylinder. Air from the cylinder is used to slowly pressurize the tank, vent cap holder, and thus the battery cap itself to a regulated level. The accumulator tank has a volume of 76 L to reduce stagnation pressure changes once the vent has opened.



a) b)

Figure 3: (a) Schematic representation of the battery vent cap holder and (b) the completed test setup installed at New Mexico Tech.

Vent opening area calculation and validation tests

Since the battery vent has the minimum cross-sectional area of the test setup and pressure in the tank is sufficiently high, airflow will choke at the vent cap. Measurement of the stagnation pressure within the tank and static pressure at the known cross-section allows for calculation of the battery vent area. A series of circular test orifices were made in various sizes to validate this measurement. Test orifices were also made with patterned holes to represent the geometries seen on actual vent caps as shown in Figure 4. These orifices are used in lieu of the battery cap during validation tests. Figure 5 shows the accuracy of orifice area calculations.

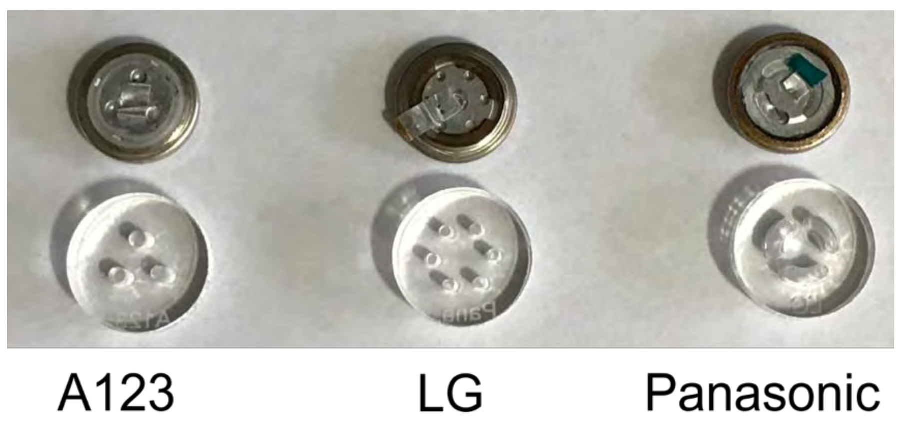


Figure 4: (above) The internal surface of battery vent caps and orifice plates made to mimic the maximum possible opening area.

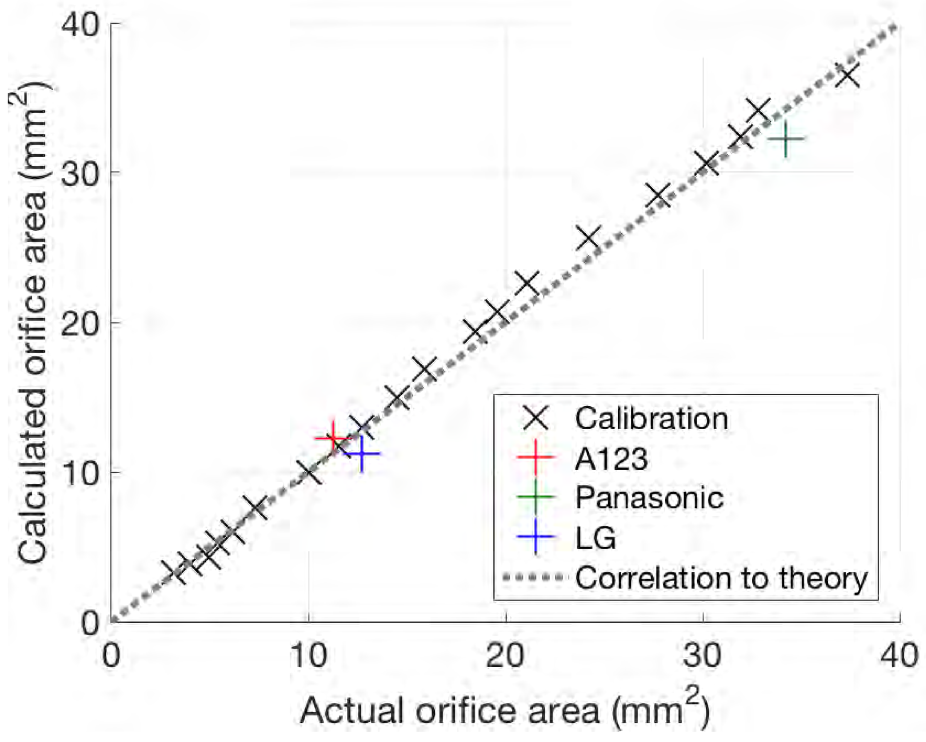


Figure 5: (right) Results of validation testing by comparing actual and calculated opening areas.

Initial testing with LG HE2 caps

The pressure limit of the accumulator tank was reached without burst of the battery vent caps. However, to provide preliminary results, caps were pressurized directly from a compressed air cylinder with a minimized flow rate. As battery vents remain open after burst, they were able to be tested with the apparatus seen in Figure 3(b). Testing results are shown in Table 1.

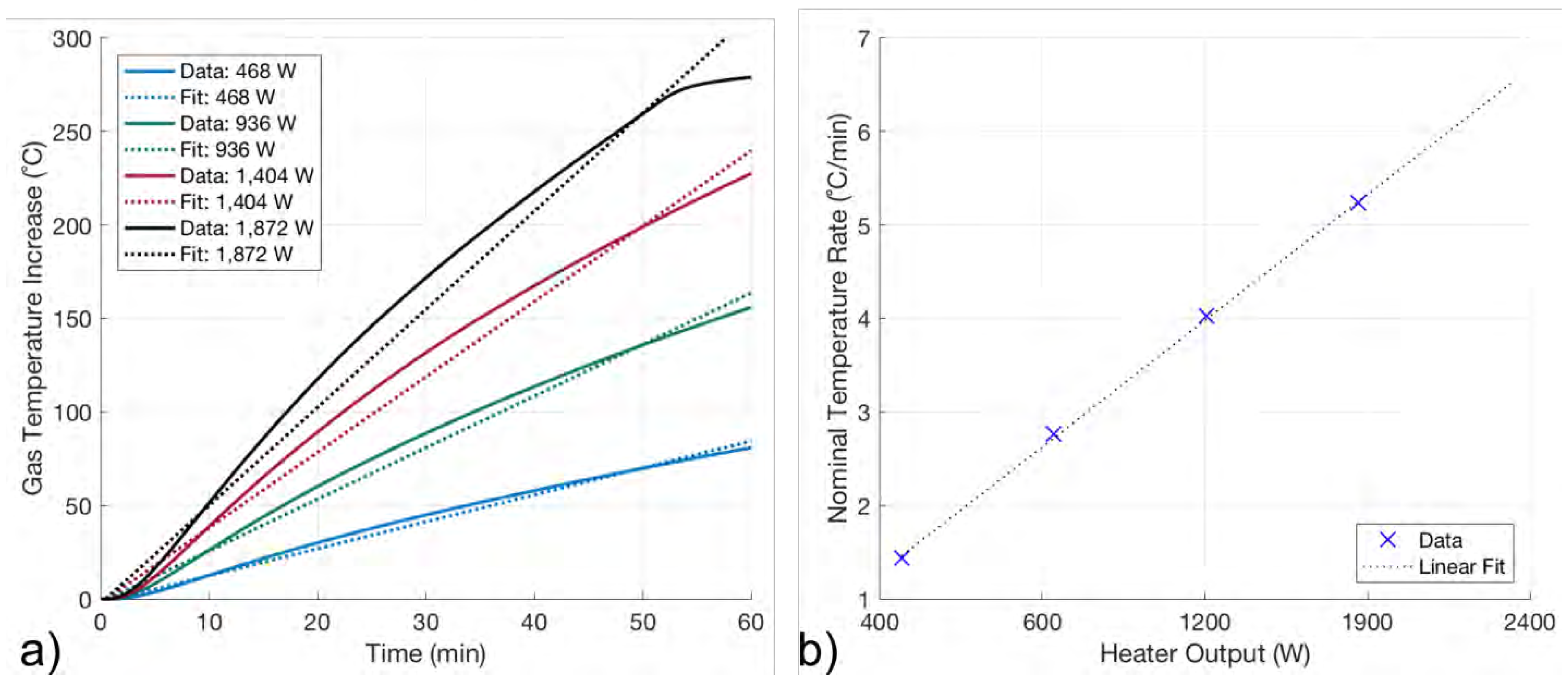
Table 1: Initial testing summary

	Burst pressure (kPa)	Opening area (mm^2)
1	1,940.9	7.3
2	1,823.7	7.1
3	1,992.6	6.5

Pressure calculation via battery case strain measurements during abuse testing

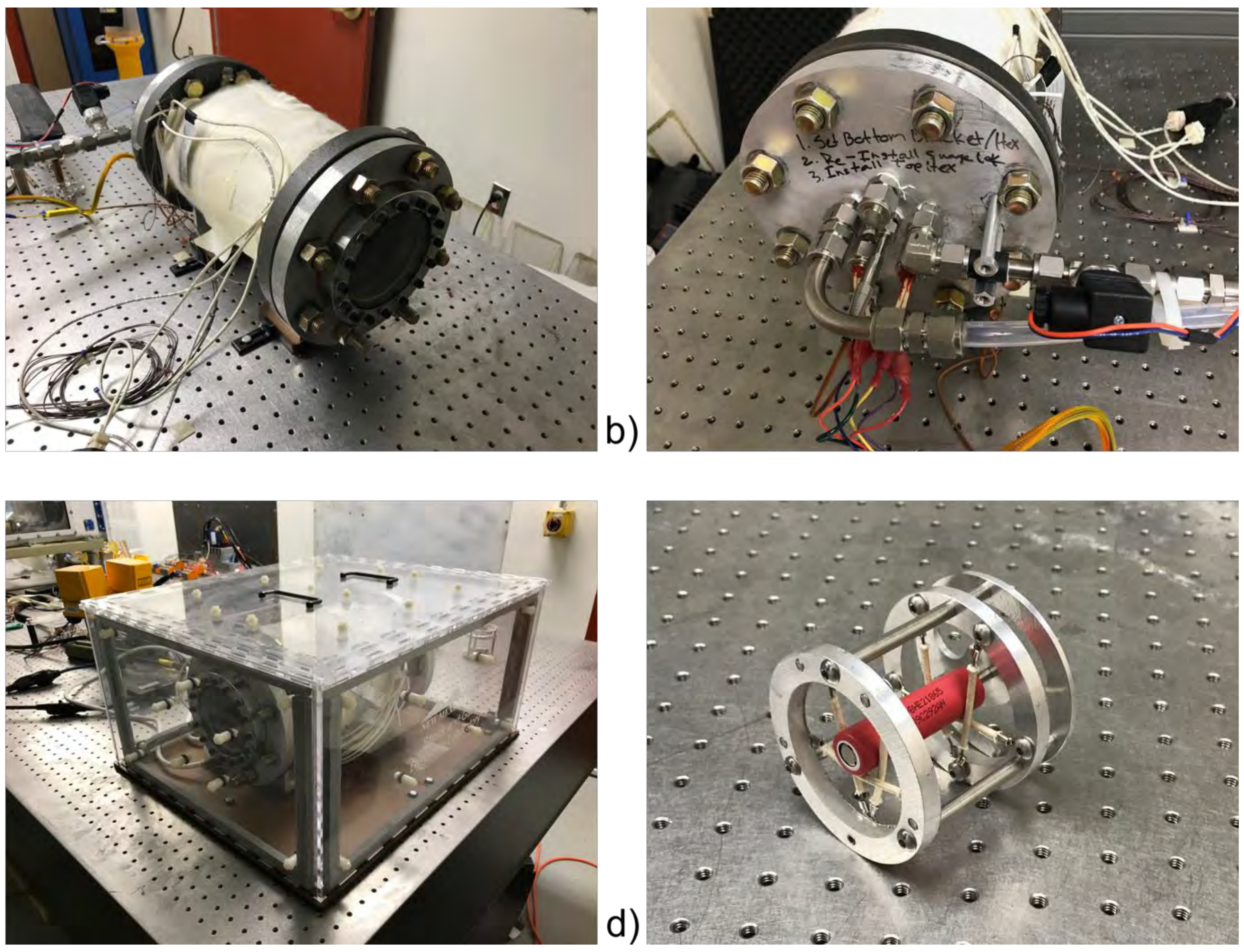
Strain gauges are used to perform noninvasive measurement of hoop and longitudinal strain of battery cases under thermal abuse conditions. Strain measurements are the sum of pressure and thermal expansion components. Internal pressure is analytically calculated from geometry, case material properties, and the two strain measurements.

A laboratory test chamber was constructed to perform these strain experiments in a thermally controlled environment as shown in Figure 7. Heating rate is aided by an insulation structure and testing in a helium environment. Measurements include battery temperature, chamber temperature and pressure, and heat flux. Heat rate calibration was performed between 468 W and 1,872 W as shown in Figure 6.



a) b)

Figure 6: Calibrations of (a) gas temperature and (b) nominal rate



a) b) c) d)

Figure 7: (a) The test chamber with viewing window, (b) instrumentation cap with a thermocouple probe, data lines, gas purge tubing, and chamber pressure transducer, (c) insulation structure, and (d) battery holder.

References and Acknowledgements

- [1] Mier et. al., Overcharge and thermal destructive testing of lithium metal oxide and lithium metal phosphate batteries incorporating optical diagnostics, J. of Energy Storage 13C (2017) pp. 378-386
- Thanks goes to Heather Barkholtz for supplying battery vent caps used in this testing.
- This work is supported by Sandia National Laboratories and funding comes from the U. S. Department of Energy Office of Electricity under contract PO 1739875.
- Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525. SAND2017-10800 C

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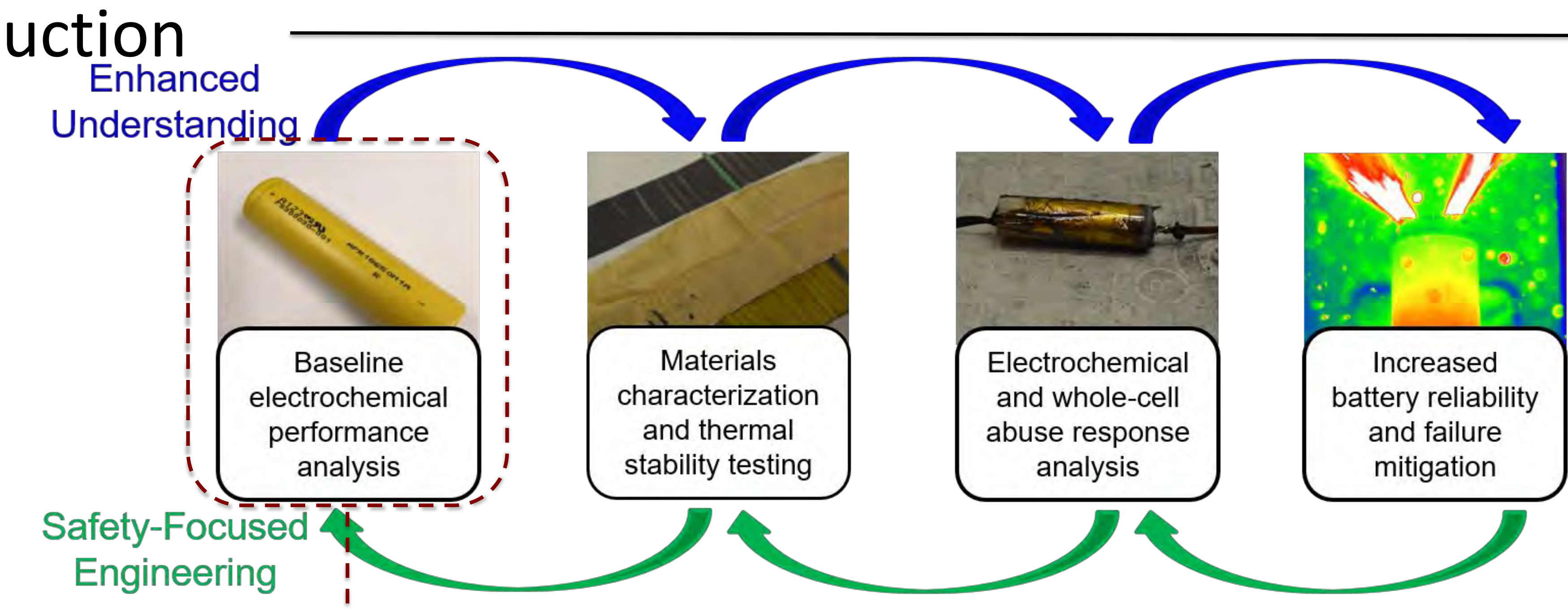
Funded by Dr. Imre Gyuk
U.S. Department of Energy; Office of Electricity; Energy Storage Systems Program

Comparative Electrochemical Performance of Commercial 18650-Format Lithium-ion Cells

Heather Barkholtz, Armando Fresquez, Babu Chalamala, and Summer Ferreira

Introduction

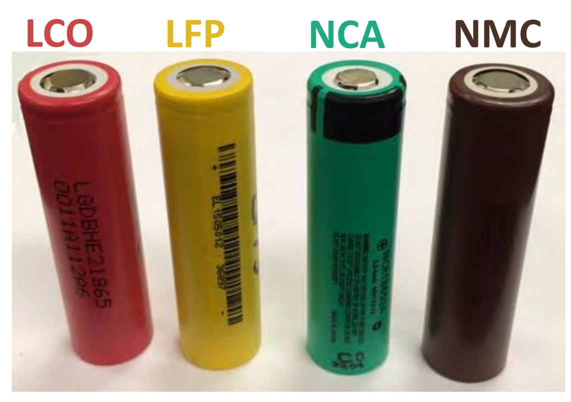
- Stationary energy storage systems (ESS) are increasingly deployed to maintain a robust and resilient grid
- As system size increases, financial and safety issues become important topics
- Holistic approach: electrochemistry, materials, and whole-cell abuse will fill knowledge gaps
- Electrochemical performance helps define safety and reliability
- Detailed studies on the electrochemical performance as a function of application conditions have been limited
- Cells have application-specific operation and performance characteristics

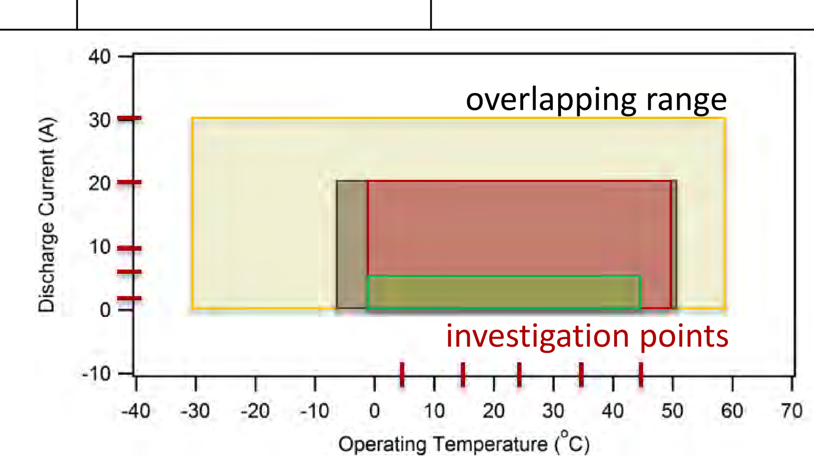


Cell Chemistry

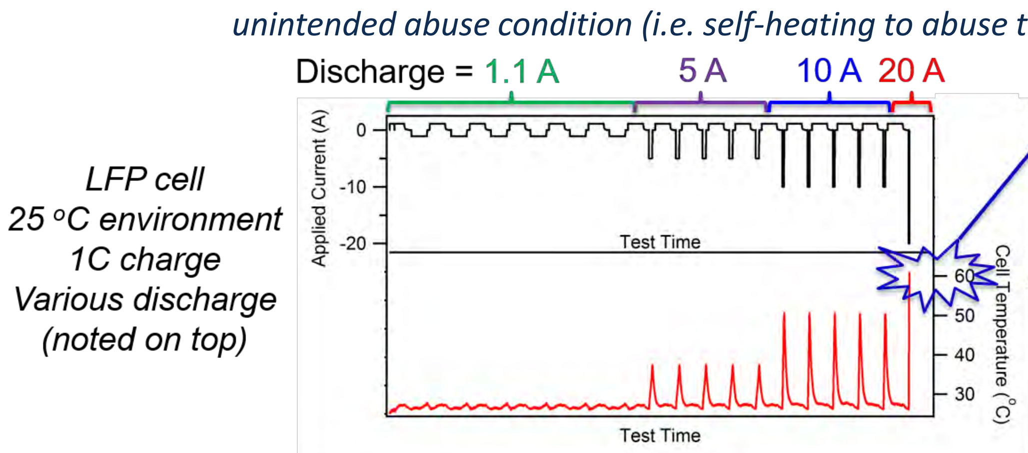
Manufacturer specifications often lack fidelity and parametric detail to ascertain the reliability and operational performance.

Battery	LCO	LFP	NCA	NMC
Cathode	$LiCoO_2$	$LiFePO_4$	$LiNi_xCo_yAl_{1-x-y}O_2$	$LiNi_{0.8}Mn_{0.15}Co_{0.05}O_2$
Capacity	2.5 Ah	1.1 Ah	2.9 Ah	3.0 Ah
Voltage	3.6 V	3.3 V	3.6 V	3.6 V
Max Discharge Current	20 A	30 A	6 A	20 A
Operating T	0-50°C	-30-60°C	0-45°C	0-50°C
Energy Density	533.3 Wh/L	212.1 Wh/L	569.7 Wh/L	612.1 Wh/L
Specific Energy	195.8 Wh/kg	88.9 Wh/kg	210.0 Wh/kg	224.8 Wh/kg
Cost per Capacity	852.3 $/kWh	2842.8 $/kWh	835.1 $/kWh	594.0 $/kWh





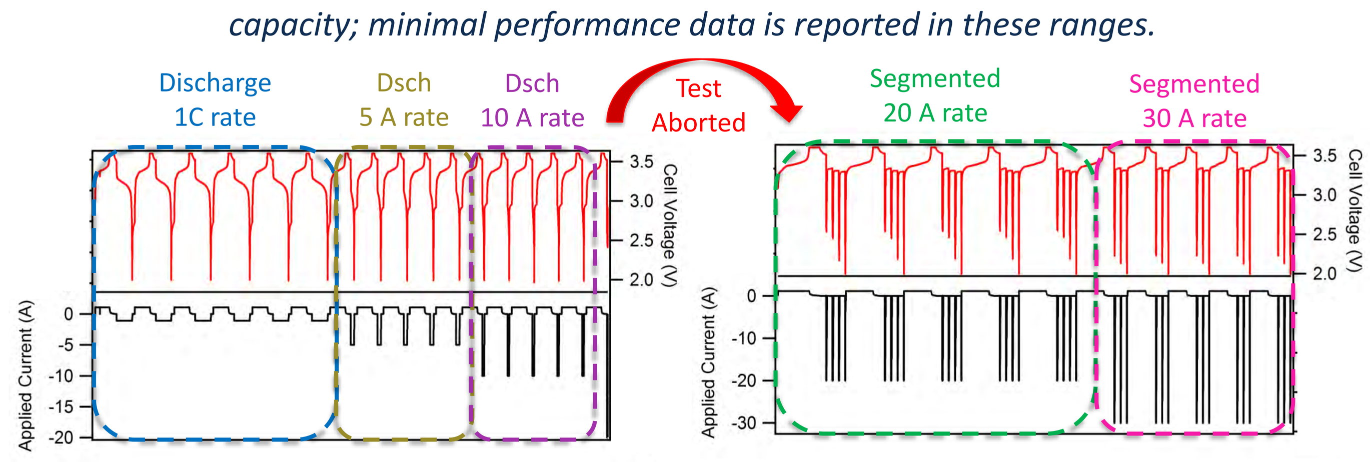
Compounding conditions such as discharge current and temperature can interact to create an unintended abuse condition (i.e. self-heating to abuse temperature).



Current = 20 A (max = 30 A)
Environment = 25 °C
Cell skin Temp = 60 °C!!!
Test Aborted!!!
Most packs don't monitor individual cell temperatures. This creates an unintended abuse condition under 'normal' operation.

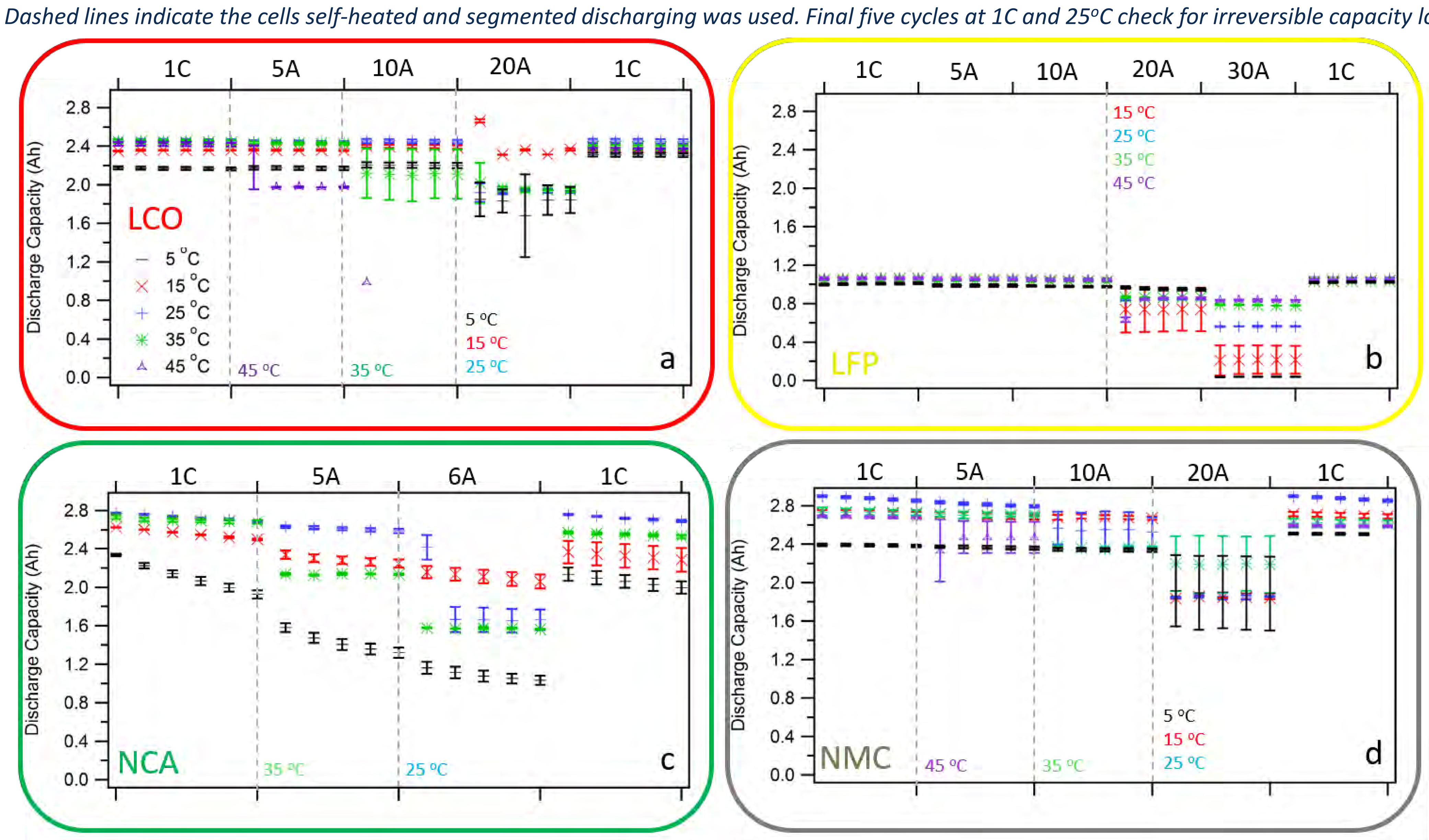
Test Procedure

Operation guidelines include temperature, maximum charging/discharging currents, and nominal capacity; minimal performance data is reported in these ranges.

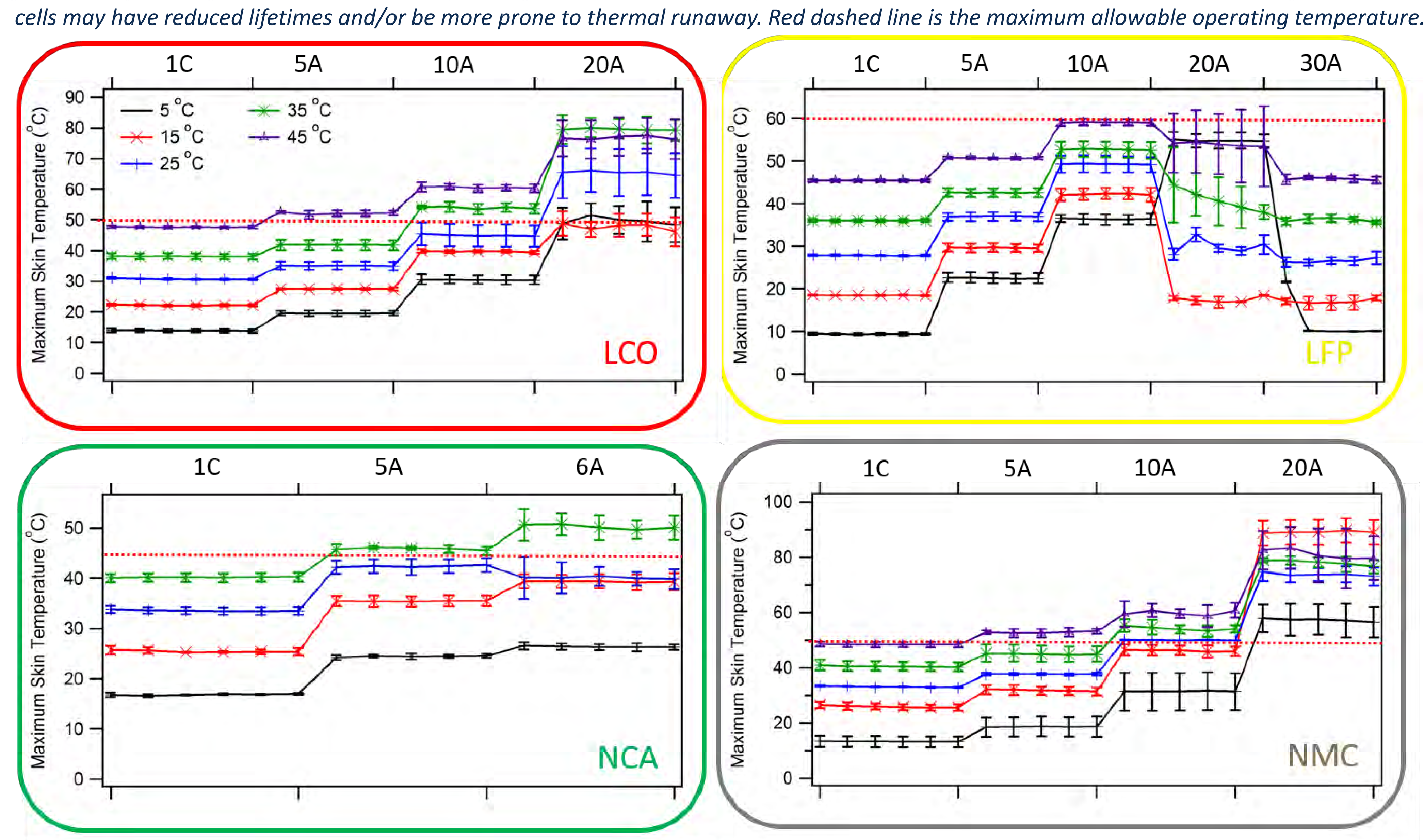


Performance

Environment temperature and discharge current have a profound effect on performance, most of which is reversible (exception: NCA and NMC). Dashed lines indicate the cells self-heated and segmented discharging was used. Final five cycles at 1C and 25°C check for irreversible capacity loss.



Significant self-heating occurs within normal operating conditions. Abuse temperatures leave cells in an unknown, potentially damaged state. These cells may have reduced lifetimes and/or be more prone to thermal runaway. Red dashed line is the maximum allowable operating temperature.



Acknowledgements:

- Funded by Dr. Imre Gyuk through the U.S. Department of Energy; Office of Electricity
- A special thanks to the following people for thoughtful discussions, advice, and experiment design:
- Loraine Torres-Castro • Randy Shurtz • Josh Lamb • John Hewson

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Conclusions

- Notable deviations in performance vs. chemistry, must consider application requirements
- Must carefully study compounding conditions to avoid unintended abuse conditions
- Some conditions caused irreversible capacity loss resulting in lifetime decay
- Without detailed performance data, safety and reliability is not fully understood

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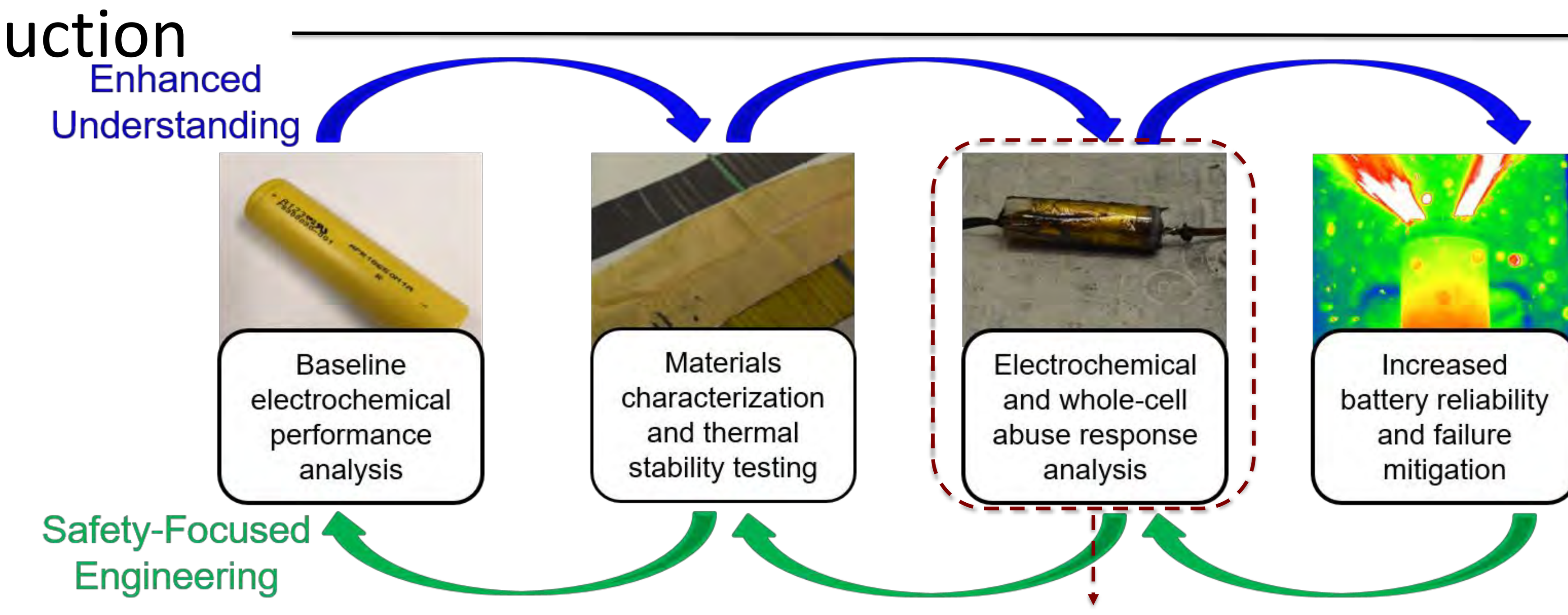
Estimating Lithium-ion Battery Fire Behavior from ARC data Using CFAST Fire Model

Heather Barkholtz, Alice Muna, Ethan Sena, Chris LaFleur, John Hewson, Josh Lamb, Jill Langendorf, Babu Chalamala, and Summer Ferreira

Introduction

- Stationary energy storage systems (ESS) are increasingly deployed to maintain a robust and resilient grid
- As system size increases, financial and safety issues become important topics
- Holistic approach: electrochemistry, materials, and whole-cell abuse will fill knowledge gaps
- A key issue in lithium-ion battery safety is quantifying effectiveness of water suppression techniques
- Tools must be explored to estimate sprinkler response to rack fires of various chemistry, SOC, and number of cells involved

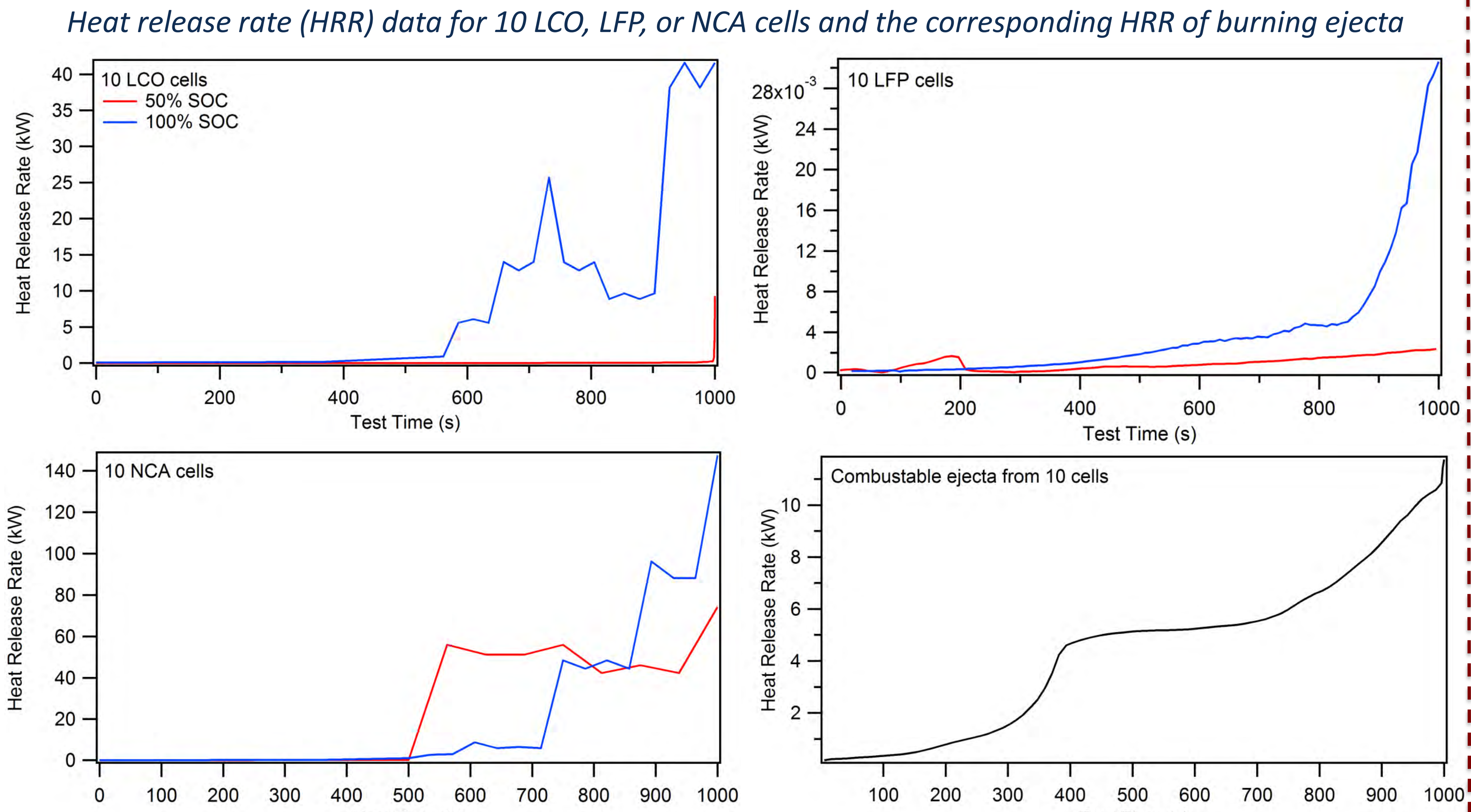


Input Data

Easily obtainable ARC data was used to estimate the heat release rate (HRR) of rack fires with various cell chemistry, SOC, and amount of cells involved

Battery	LCO	LFP	NCA
Cathode	$LiCoO_2$	$LiFePO_4$	$LiNi_xCo_yAl_{1-x-y}O_2$
Nominal capacity (Ah)	2.5	1.1	2.9
Specific energy density (Wh kg^{-1})	195.8	88.9	210.0
Energy Density (Wh L^{-1})	533.3	212.1	569.7
HRR_{max} at 100% SOC (kW)	0.031	41.6	147.6
HRR_{max} at 50% SOC (kW)	0.0023	9.3	74.3

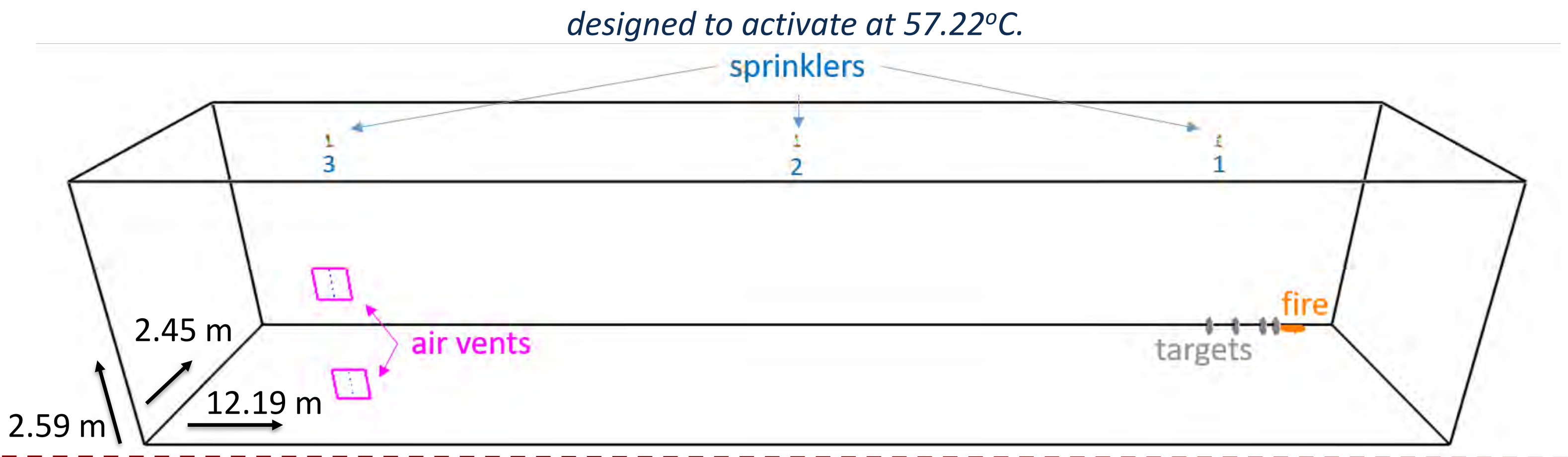
Heat release rate (HRR) data for 10 LCO, LFP, or NCA cells and the corresponding HRR of burning ejecta



Test Input Conditions					
Cell Chemistry	Cell SOC		Amount of Cells		
LCO	50%	100%	10	50	100
LFP	50%	100%	10	50	100
NCA	50%	100%	10	50	100

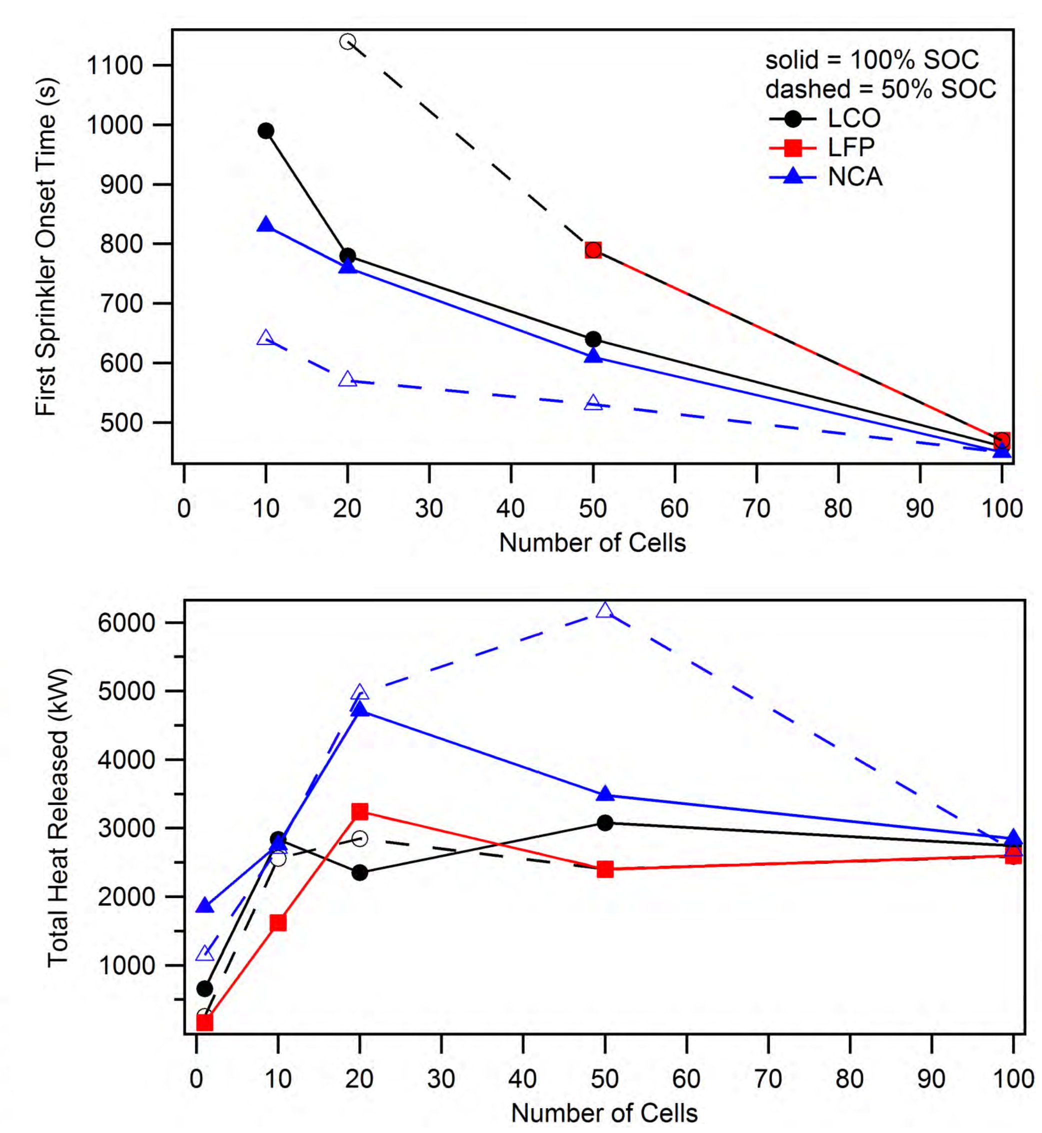
ISO Container

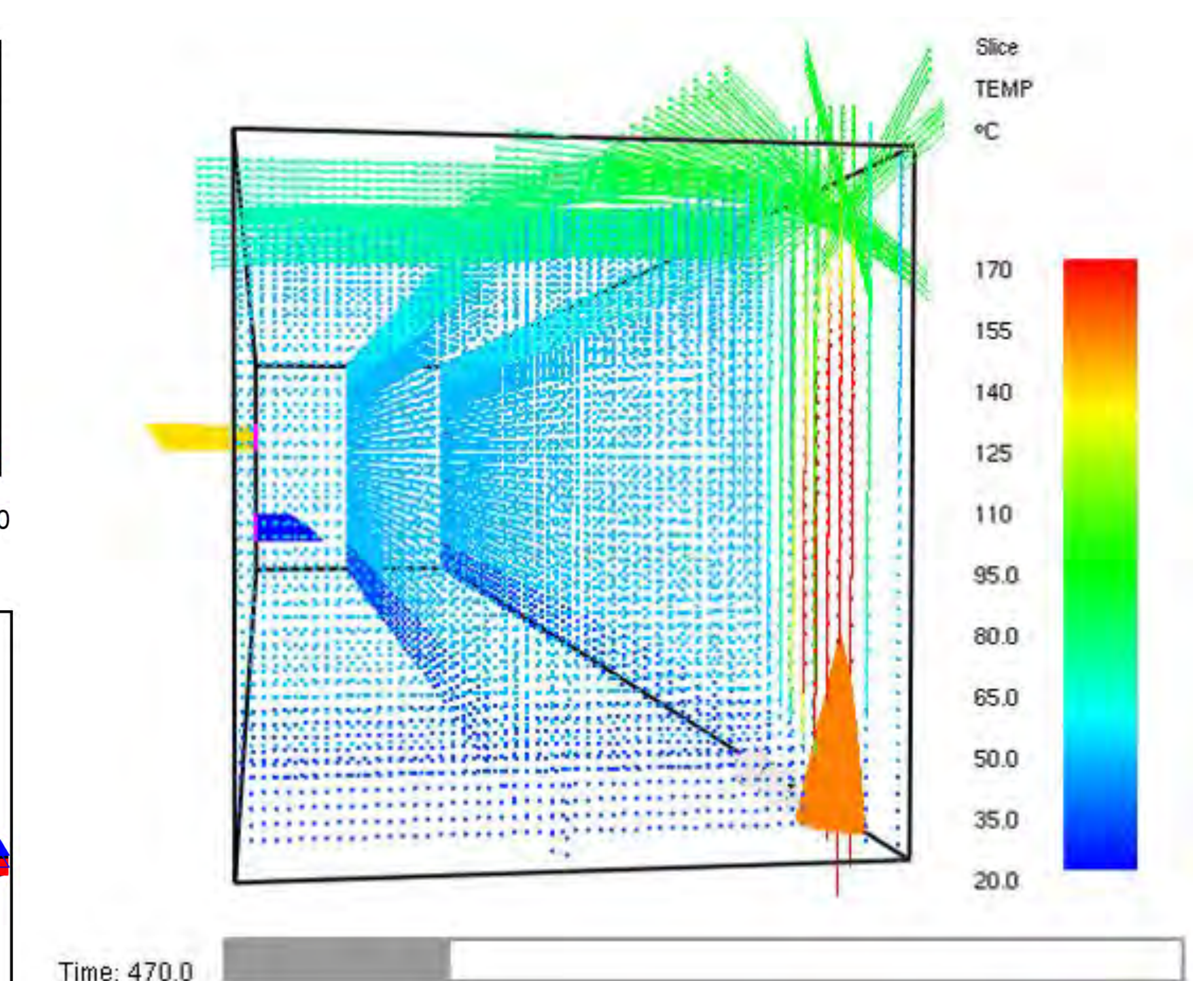
Schematic of the ISO container used in this work. The fire was located in the corner, there are targets to monitor heat flux at 6, 12, 24, and 36 inches from the center of the fire. Three sprinkler heads are designed to activate at 57.22ºC.



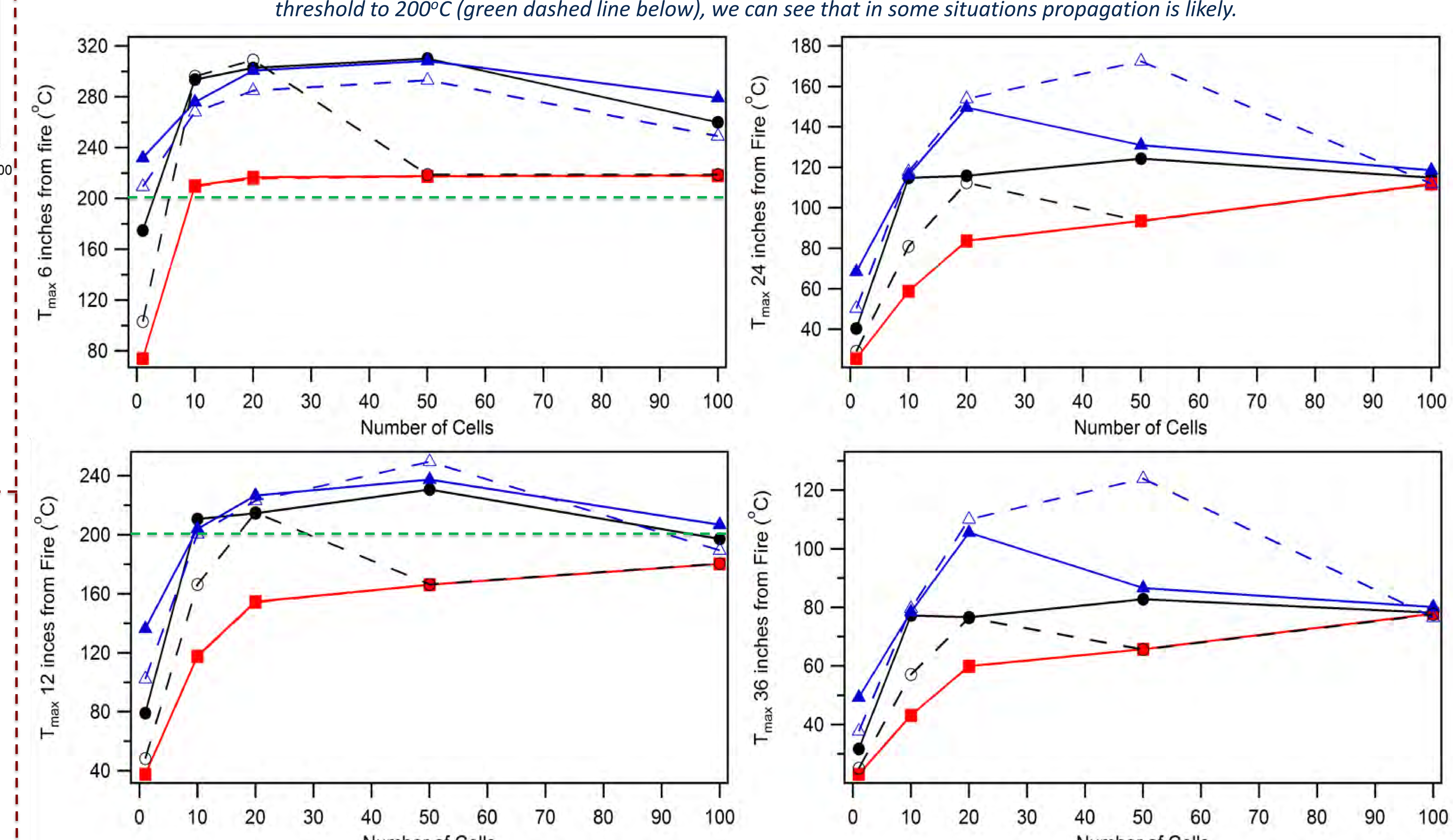
CFAST Fire Model Results

Sprinkler onset time is crucial in determining the total heat release rate and the success of the sprinkler system.





Targets were placed 6, 12, 24, and 26 inches from the center of the fire to measure heat flux and temperature. This was done to estimate the likelihood of fire propagation throughout a module, rack, or the ISO container. Sprinkler activation continued normally as in other tests. If we set the propagation threshold to 200ºC (green dashed line below), we can see that in some situations propagation is likely.



Conclusions

- Earlier sprinkler onset time yields lower total heat release rates, less sprinklers activating, and a more controlled fire.
- At 24 and 36 inches from the fire, no fire propagation situations were likely
- Sprinkler response can be screened with CFAST and ARC data prior to more elaborate testing

Acknowledgements:
- Funded by Dr. Imre Gyuk through the U.S. Department of Energy; Office of Electricity
- A special thanks to the following people for thoughtful discussions, advice, and experiment design:
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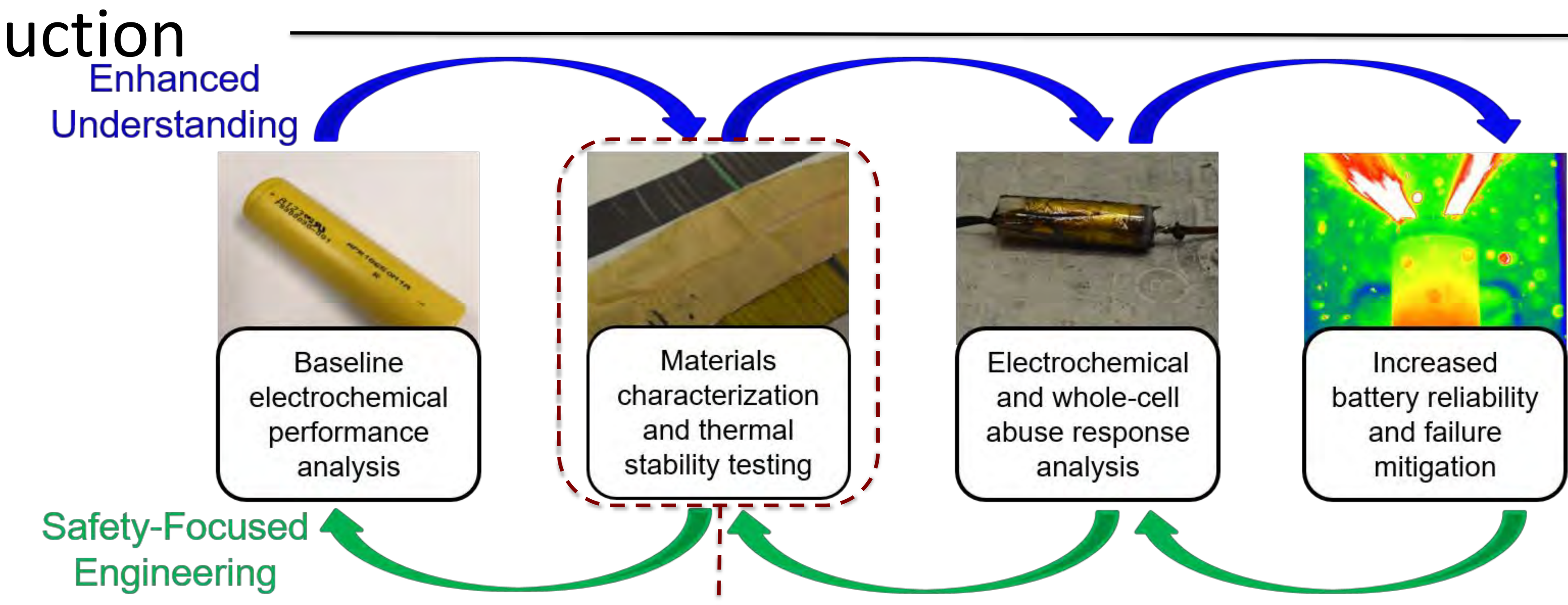
Multi-scale Thermal Stability Study of Lithium-ion Batteries as a Function of Chemistry and State of Charge

Heather Barkholtz, Sergei Ivanov, Jill Langendorf, Josh Lamb, Babu Chalamala, and Summer Ferreira

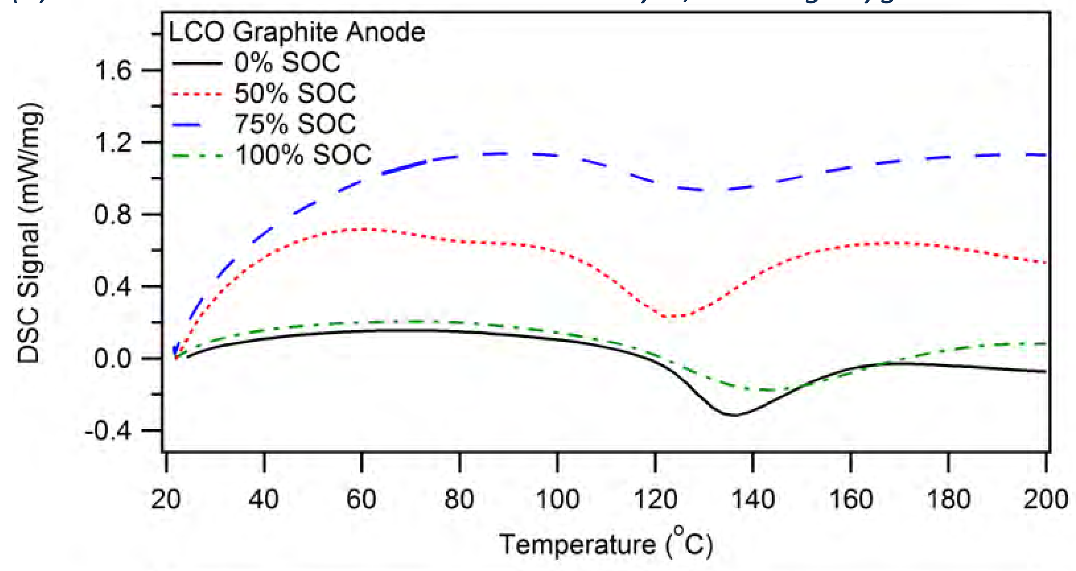
Introduction

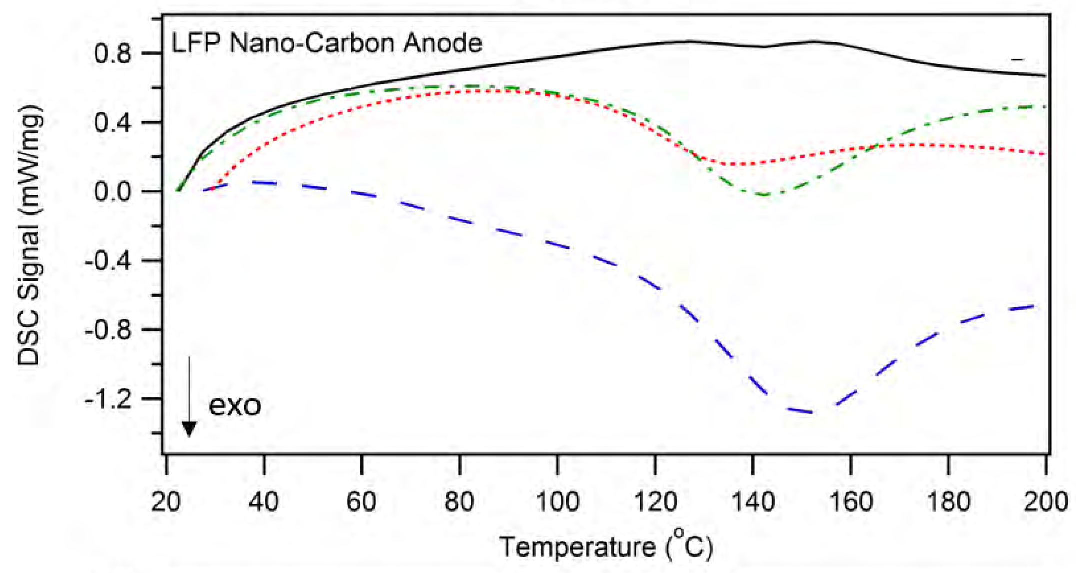
- Stationary energy storage systems (ESS) are increasingly deployed to maintain a robust and resilient grid
- As system size increases, financial and safety issues become important topics
- Holistic approach: electrochemistry, materials, and whole-cell abuse will fill knowledge gaps
- The few studies on commercial lithium-ion battery thermal stability focus on whole cell failure without component analysis
- A deeper understanding of commercial cell thermal runaway is required to develop failure mitigation strategies and/or inherently safe cells

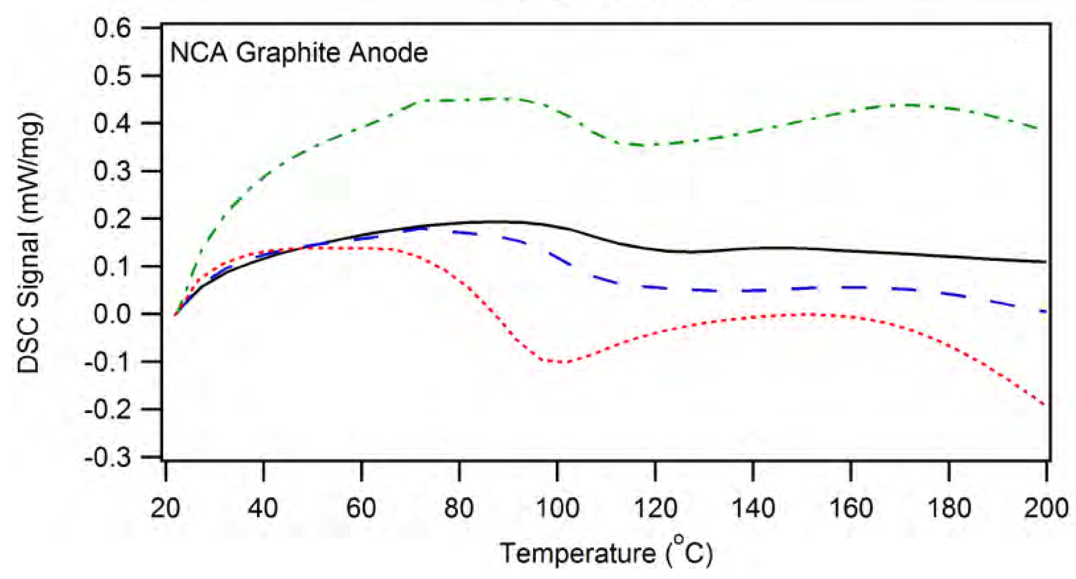


Anode Failure

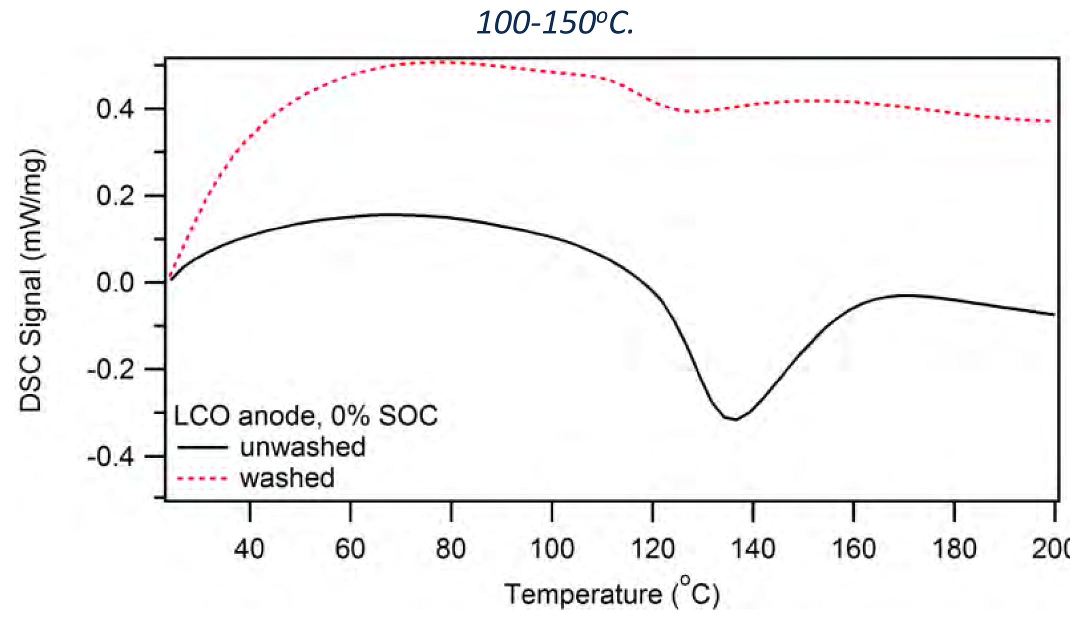
The thermal runaway process can be generally broken into two main steps:
(1) Decomposition of solid-electrolyte interface and reaction between intercalated lithium ions and electrolyte
(2) Reaction between cathode and electrolyte, evolving oxygen and heat







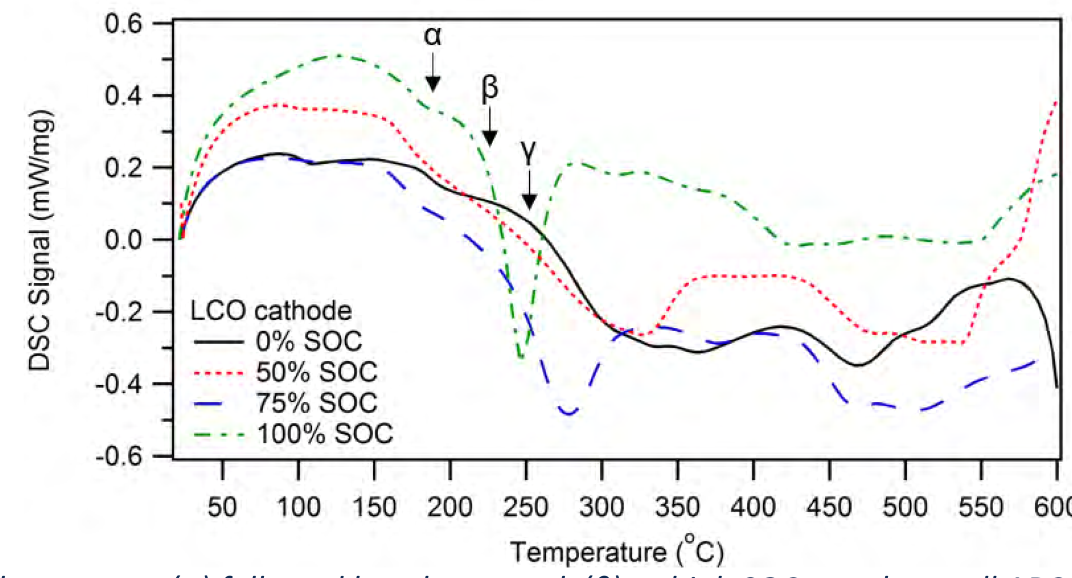
DSC measurements on anode materials show an exothermic peak with onset between 100-150°C.



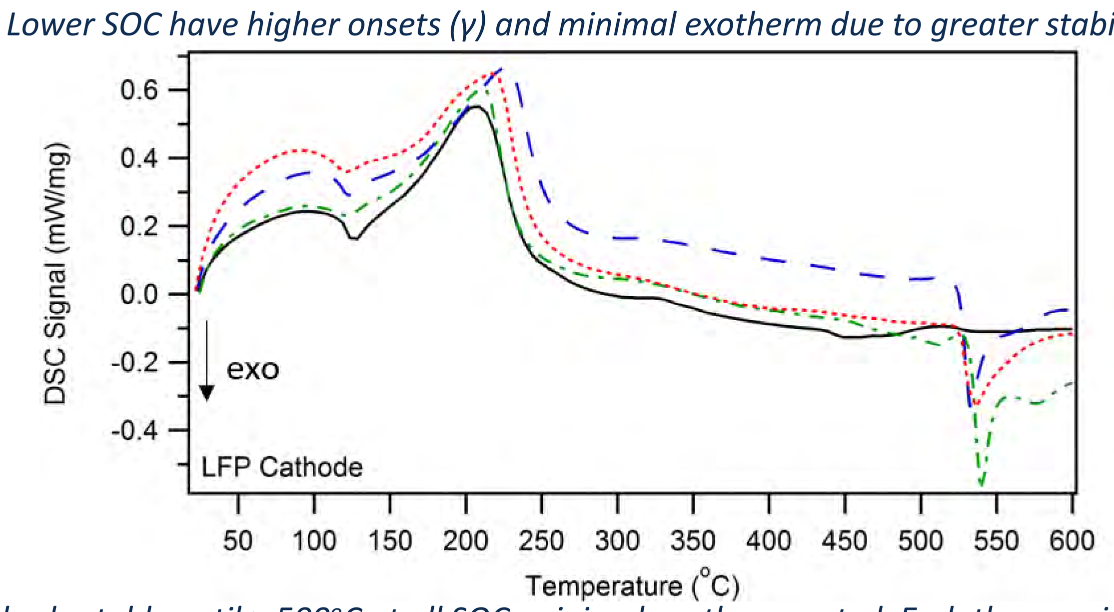
Exothermic peak is from metastable SEI + electrolyte decomposition. Washing the anode in DMC removes metastable SEI/electrolyte and also eliminates the exotherm.

Cathode Failure

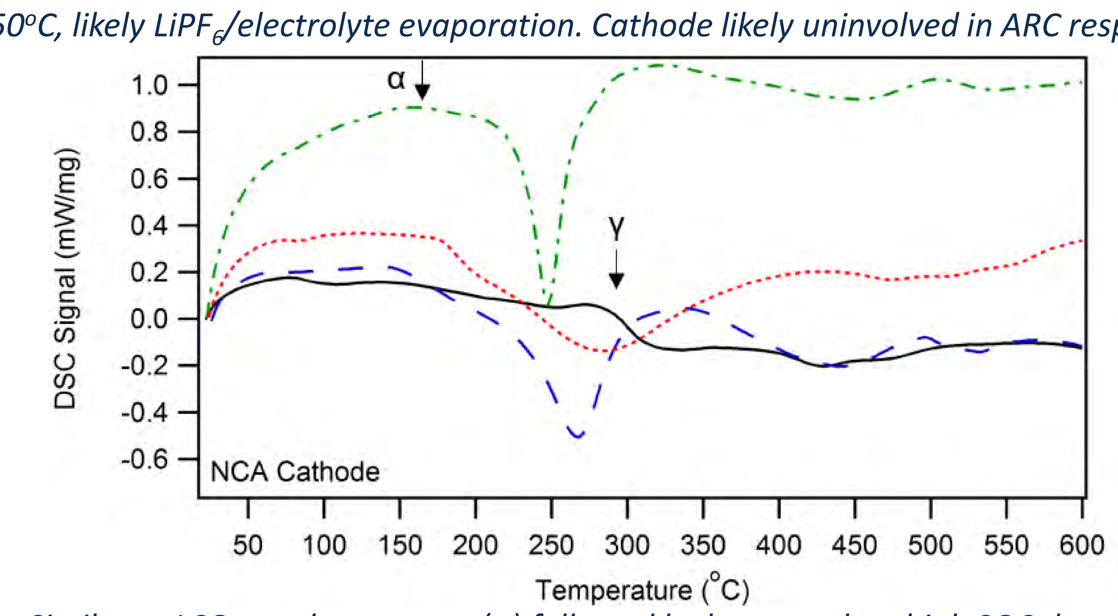
Cathode decomposition reaction is detected in ARC by a sudden, large increase in self heating (T_{cath}). The cathode decomposition is also responsible for HR_{max}.



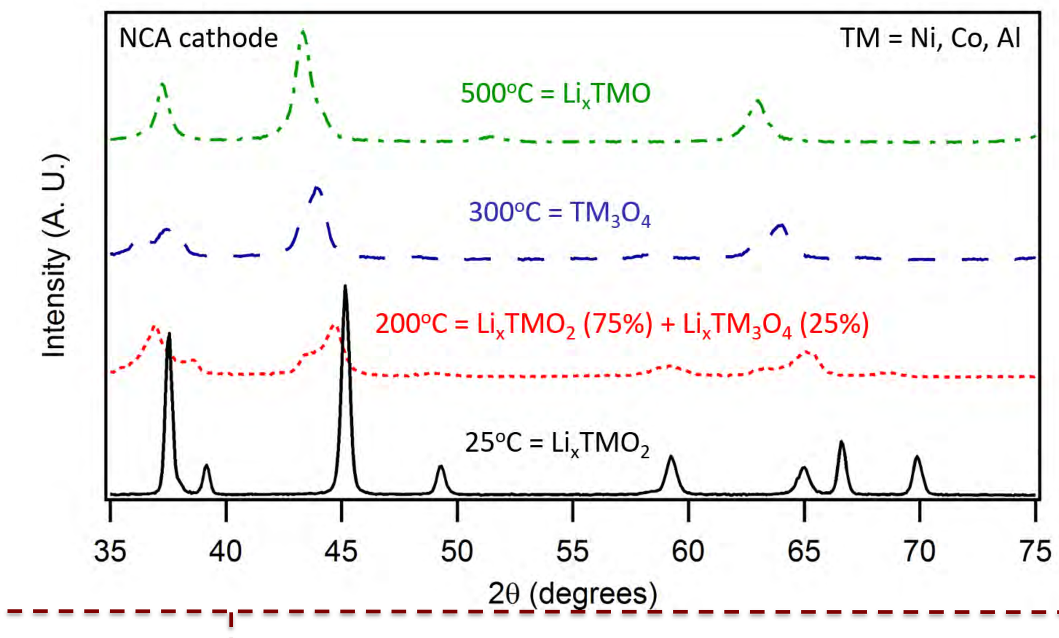
Exotherm onset (α) followed by a large peak (β) at high SOC matches well ARC and XRD. Lower SOC have higher onsets (γ) and minimal exotherm due to greater stability



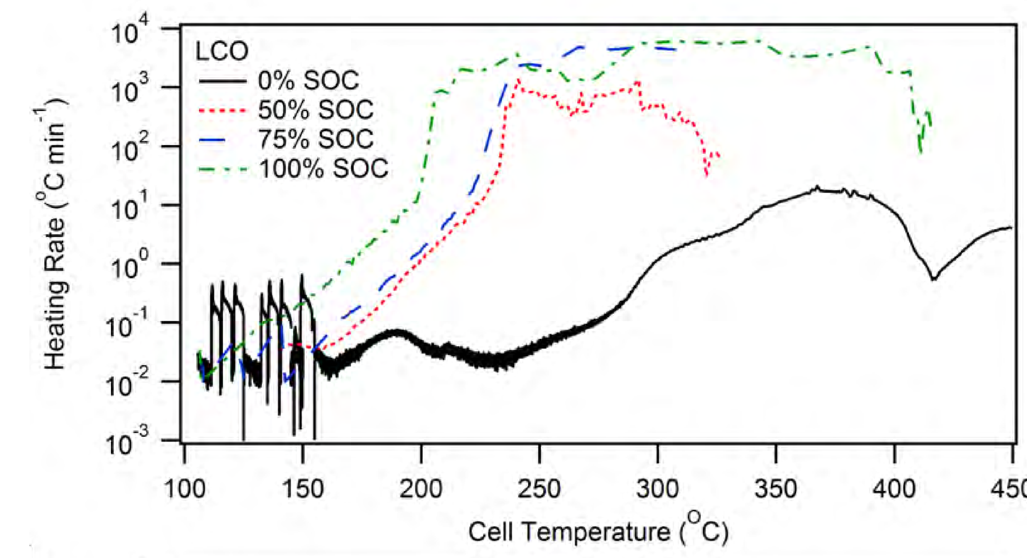
Cathode stable until > 500°C at all SOC, minimal exotherm noted. Endotherm exists 125-250°C, likely $LiPF_6$/electrolyte evaporation. Cathode likely uninvolved in ARC response.

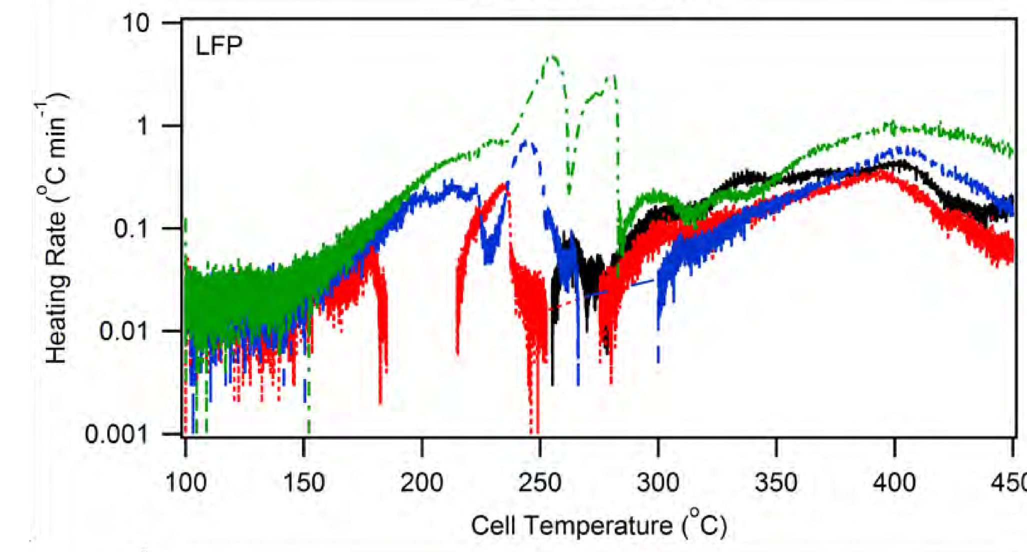


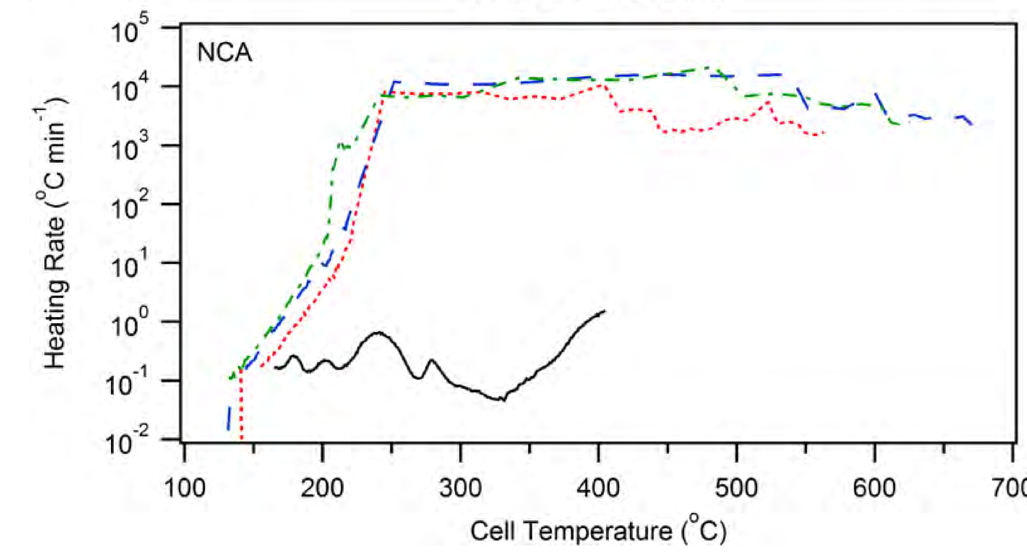
Similar to LCO, exotherm onset (α) followed by large peak at high SOC due to metastability of delithiated layered metal oxides. Lower SOC cathodes are stable (γ).



Whole Cell Failure







Cell	SOC (%)	T_{onset} (°C)	T_{exo} (°C)	HR_{max} (°C min^{-1})	$HR_{max,norm}$ (°C min^{-1} Ah^{-1})
LCO	0	105.8	298.1	18.4	7.4
	50	106.2	197.8	1361.1	544.4
	75	106.5	169.4	4822.3	1928.9
	100	106.4	168.4	6053.5	2421.4
LFP	0	105.9	---	0.4	0.4
	50	100.8	---	0.3	0.3
	75	100.7	---	0.7	0.6
	100	100.9	240.5	4.5	4.1
NCA	0	164.9	391.8	1.5	0.5
	50	140.7	182.2	10810.3	3603.4
	75	131.7	169.4	16107.4	5369.1
	100	132.5	165.9	21480.4	7160.1

T_{onset} = HR > 0.033°C min^{-1} T_{exo} = HR > 1°C min^{-1}

Conclusions

- Variability in ARC (T_{onset}, T_{cath}, & HR_{max}) can be traced back to cell component chemistry and SOC
- SEI decomposition is the onset of thermal runaway
- Stable cathodes (LFP at all SOC, LCO and NCA at 0% SOC) do not contribute to ARC heating rates
- Metastable (delithiated) cathodes decompose energetically at lower temperatures
- NCA releases the most O_2 at low temperatures (< 200°C), resulting in large HR_{max} values

Acknowledgements:
- Funded by Dr. Imre Gyuk through the U.S. Department of Energy; Office of Electricity
- A special thanks to the following people for thoughtful discussions, advice, and experiment design:
- Loraine Torres-Castro • Randy Shurtz • Josh Lamb • John Hewson

U.S. DEPARTMENT OF ENERGY
NNSA National Nuclear Security Administration

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SAND No. SAND2017-9828 C

Investigation and Optimization of Sodium Metal Halide Batteries (Na-MH) at Intermediate Temperature

Hee Jung Chang[1], Xiaochuan Lu[1], Jeff F. Bonnett[1], Keeyoung Jung[2], Vincent L. Sprenkle[1] and Guosheng Li[1,*]

[1]Electrochemical Materials and Systems Group, Pacific Northwest National Laboratory (PNNL), Richland, Washington, USA
[2]Materials Research Division, Research Institute of Industrial Science and Technology (RIST), Pohang, South Korea

Pacific Northwest NATIONAL LABORATORY

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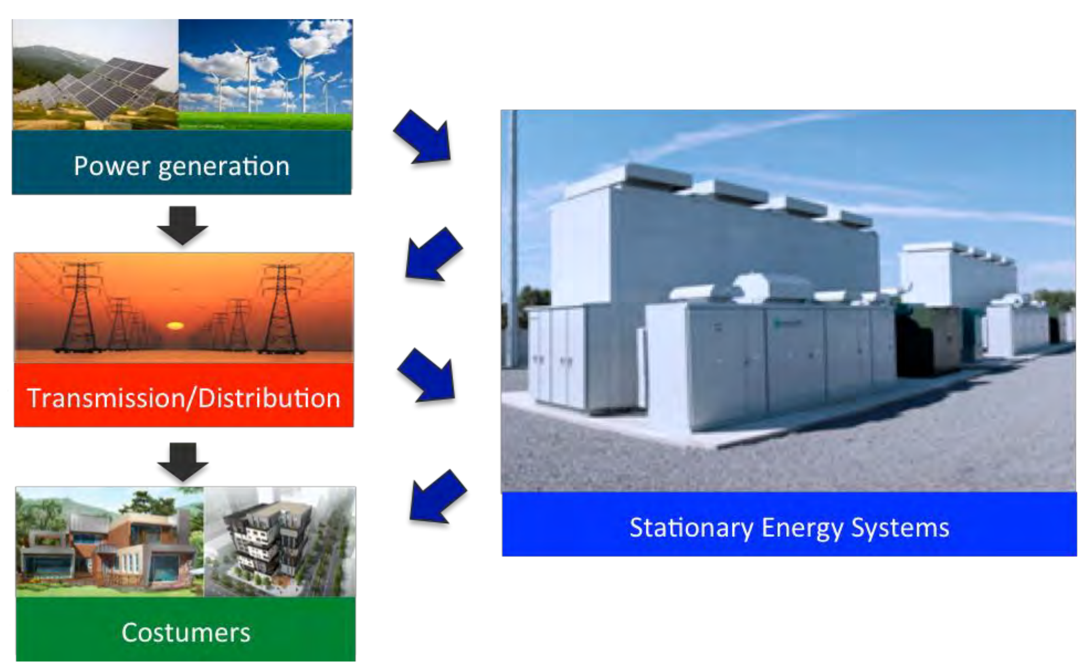
Introduction: In recent years, stationary energy storages have been receiving a high degree of attention due to its critical roles for integrating renewables, improving electricity grid reliability and resiliency, and enhancing efficiency of electricity utilization through smart grid, etc. Under the international collaborating research project co-supported by government agencies – DOE (US) and KETEP (South Korea), PNNL and RIST are developing intermediate temperature (IT) sodium-metal halide (Na-MH) battery technology.

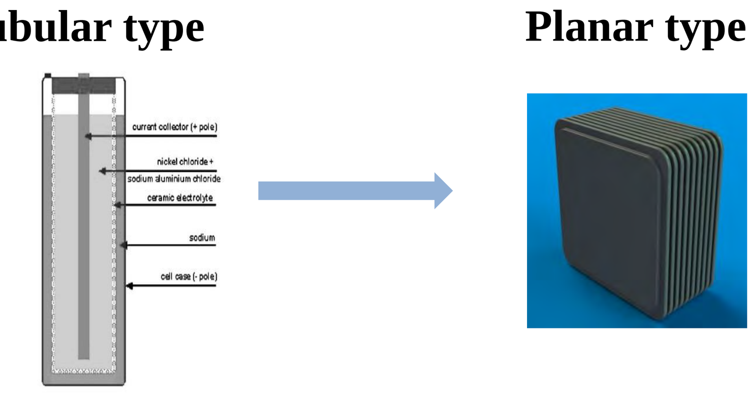
Owing to its long cycle life, low cost, high energy density, and superior battery safety, IT Na-MH battery could be one of the most promising battery technologies that can fulfill the demands of applications from residential to large-scale stationary energy storage systems.



Sodium-Metal Halide Battery (ZEBRA battery)

$$2NaCl + Ni \underset{\text{Discharge}}{\overset{\text{Charge}}{\rightleftharpoons}} 2Na + NiCl_2 \ (2.58\ V)$$

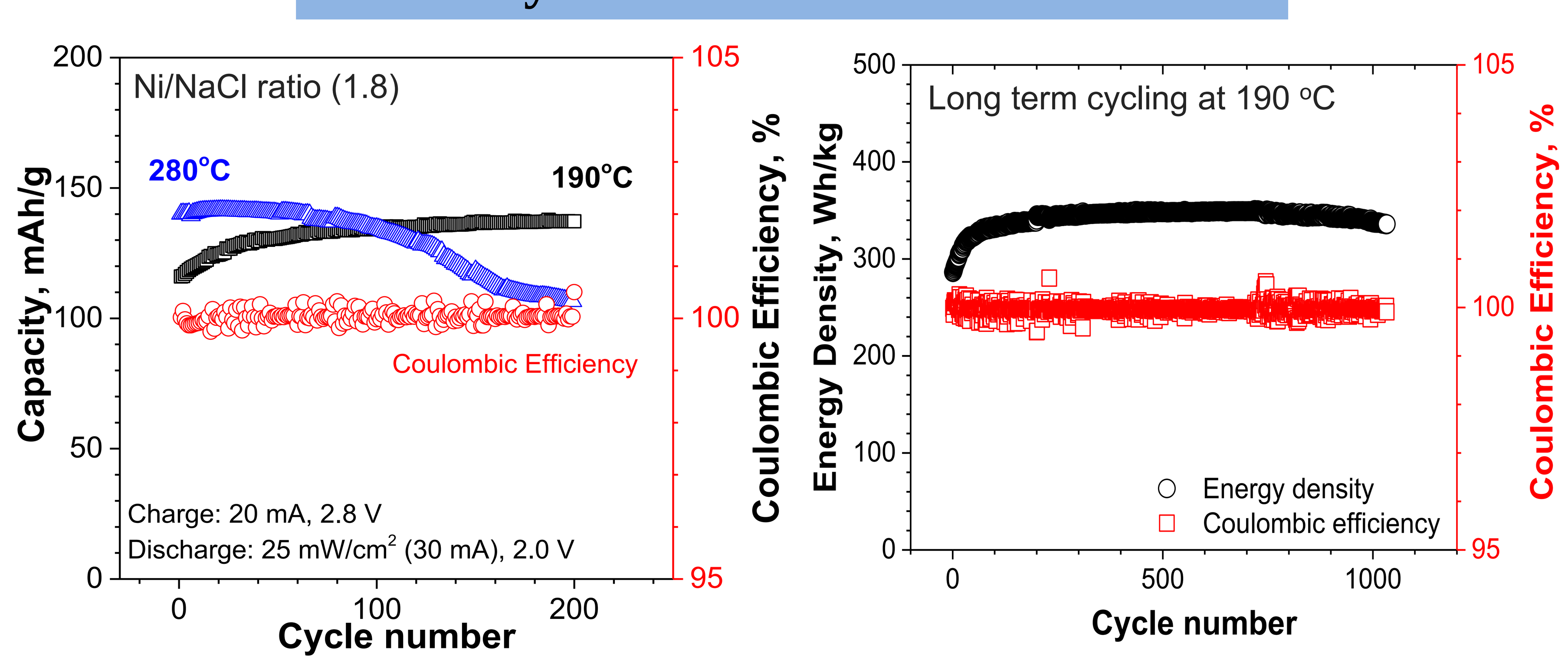
Tubular type **Planar type**



Current challenges & **PNNL Approaches**

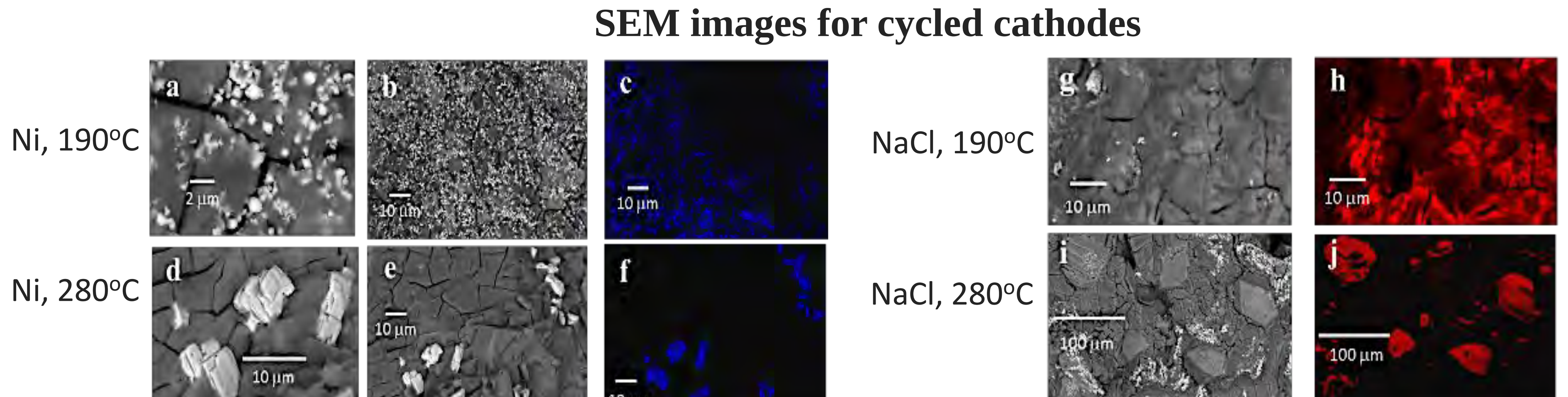
	Tubular	Planar
Cell architecture	High cost	Low cost
Cell degradation	Fast	Slow
Materials	High cost	Low cost

1. Battery Performance 190°C vs 280°C[1]



- Remarkable electrochemical performance can be achieved even at an intermediate temperature (IT) of 190 °C with high energy density of **350 Wh/kg.** (233 Wh/kg w/ melts) and high energy efficiency of **92%** while faster degradation observed at high T of 280 °C.
- Excellent stability shown **over 1000** cycles. (1 year and 6 months)

SEM images for cycled cathodes

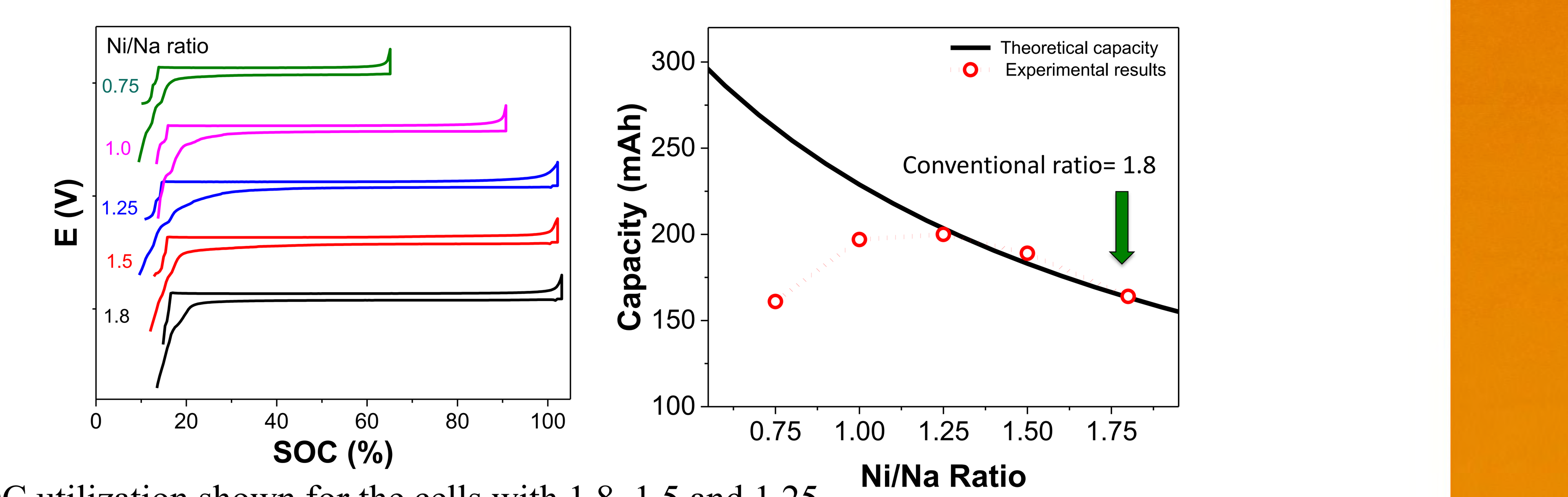


The initial particle sizes: Ni (1~2 μm) and NaCl (~30 μm)

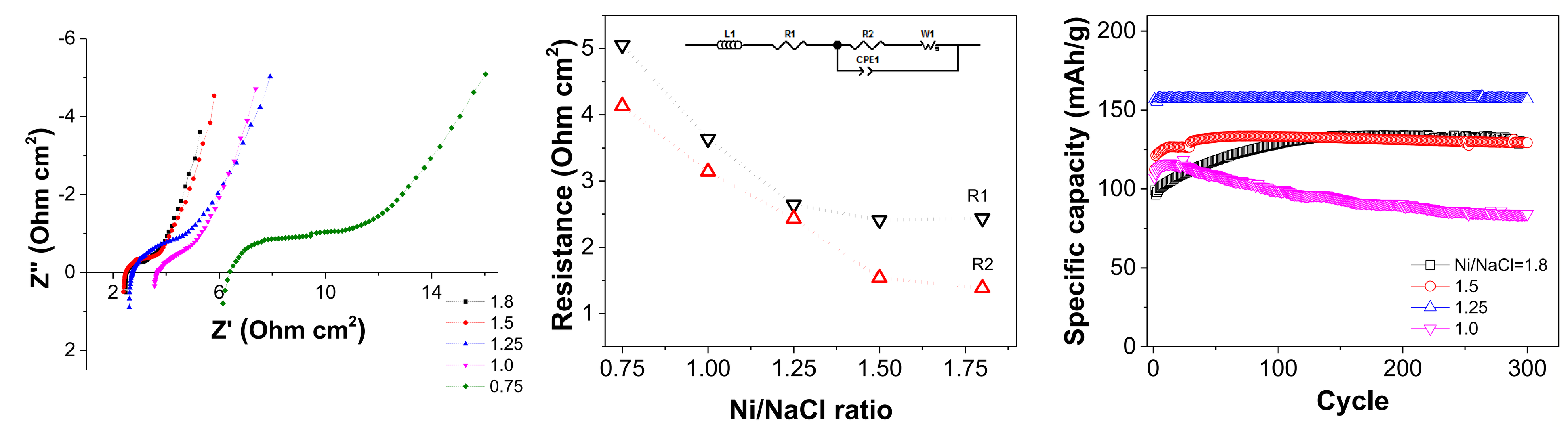
- Significant growth of cathode particles observed in the cell at high T, resulting in the cell degradation due to a loss of active area of Ni and sluggish dissolution of NaCl.

2. Ni-less cathode at 190°C[2]

Plot of cell performances with different Ni/NaCl ratios in cathode



- 100% SOC utilization shown for the cells with 1.8, 1,5 and 1,25.
- 1.25 Ni/NaCl ratio shows the highest gravimetric charge capacity (as high as 181 mAh/g)
- The cells with lower Ni/NaCl ratios show lower capacities compared to theoretical values.

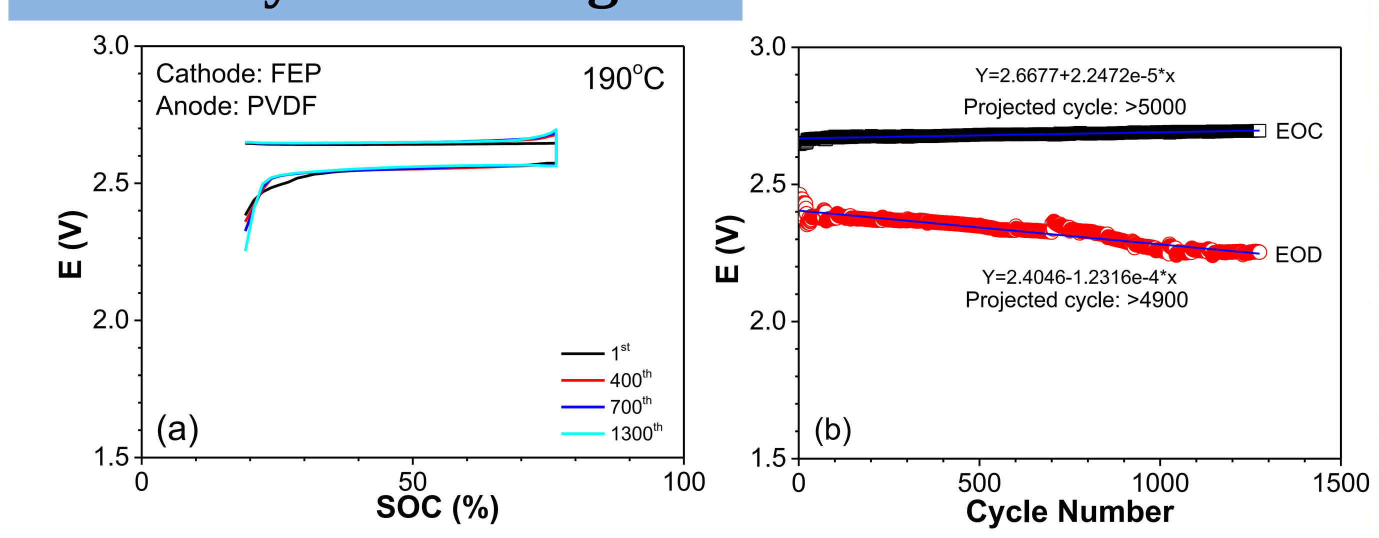


- As the Ni/NaCl rato decreases, the ohmic resistance (R1) and charge transfer resistance (R2) tend to increase, indicating the formation of an electrically less conductive $NiCl_2$ layer during cycling.
- 1.25 ratio shows an excellent cycling stability with the highest capacity of 165mAh/g over 300 cycles.

3. Polymer Sealing[3]

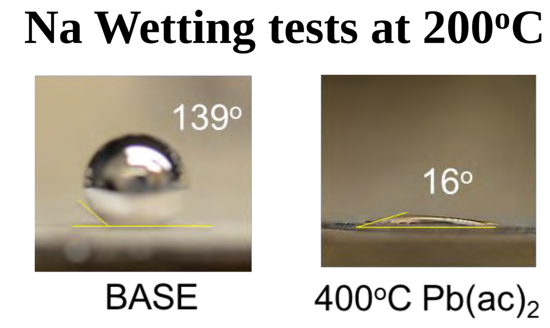
Anode:
PE, PVDF

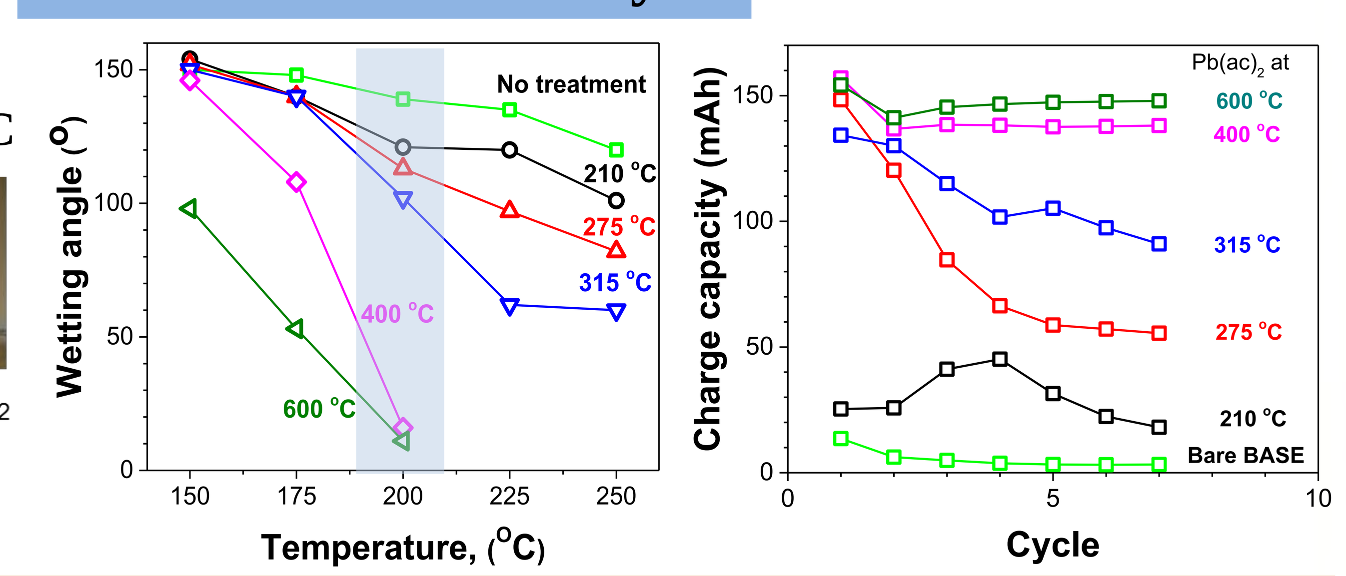
Cathode:
PE, FEP, PFA, PTFE



4. Sodium Wettability [4]

Na Wetting tests at 200°C





Summary and Perspective

- Remarkable electrochemical performance was achieved at an intermediate temperature (IT) of 190 °C with high energy density (350 Wh kg^{-1}).
- 1.25 Ni/NaCl ratio can render significant advantages, such as reducing expensive Ni cost in cathode synthesis (30% less than conventional Ni in cathode), providing higher specific capacity per mass, and excellent long term cycle stability, in particular for scaled-up battery applications.
- The implementation of conventional polymers has been demonstrated as a cost-effective, simple and practical sealing method for IT planar Na-MH batteries.
- Our results suggest that these advances can significantly reduce battery materials and manufacturing costs, and also promote the practical applications of Na-MH battery technologies in stationary energy storage systems.

Acknowledgements

This work is supported by the U.S. Department of Energy (DOE) Office of Electricity Delivery and Energy Reliability under contract No. 57558. PNNL is a operated by Battelle Memorial Institute for the DOE under contract DE-AC05-76RL01830

U.S. DEPARTMENT OF ENERGY

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References:
1. Li et al. *Nature Commun.* 7, 10683 (2016)
2. Chang et al. *(In preparation)*
3. Chang et al. *J. Power Source*. 348, 150 (2017)
   Li et al. *TechConnect Proceeding* 216 (2017)
4. Chang et al. *(In preparation)*

Update on the Natural Energy Laboratory of Hawaii Authority ESS Projects

Laurence Sombardier, Gregory Barbour, Keith Olson
Natural Energy Laboratory of Hawaii Authority (NELHA)

PEER REVIEW 2017
EVOLUTION & REVOLUTION
San Diego, California | October 9-10, 2017

NELHA

NELHA ESS TEST BED

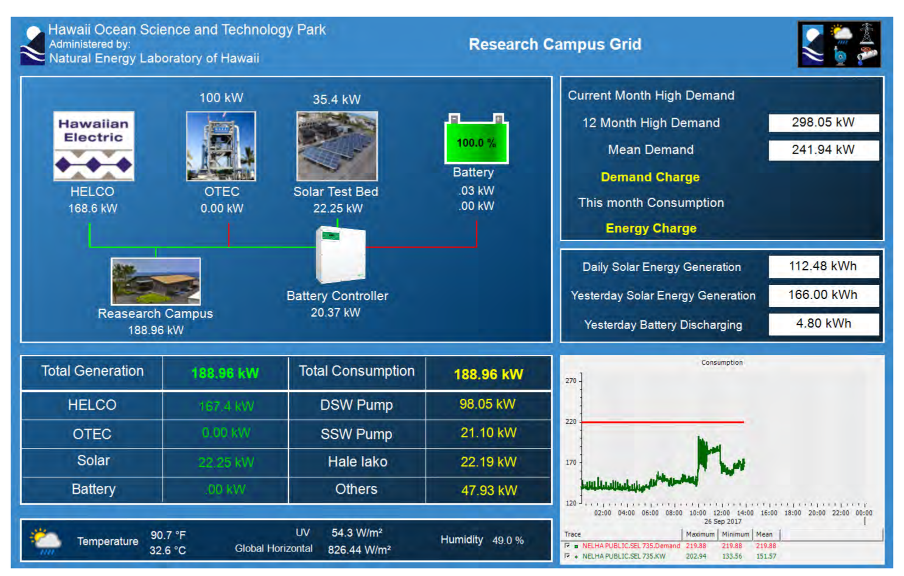
New Projects:

Company	Description	Install
ecoult	UltraFlex – 11kWh, 25kW peak power http://www.ecoult.com/	Q4 2017
APPARENT	Inverter and power management demo at Gateway http://apparent.com/	Q4 2017
stem	Energy management software and lithium ion batteries (36 kW, 72 kWh) http://www.stem.com/	Q1 2018

MICROGRID DEVELOPMENT

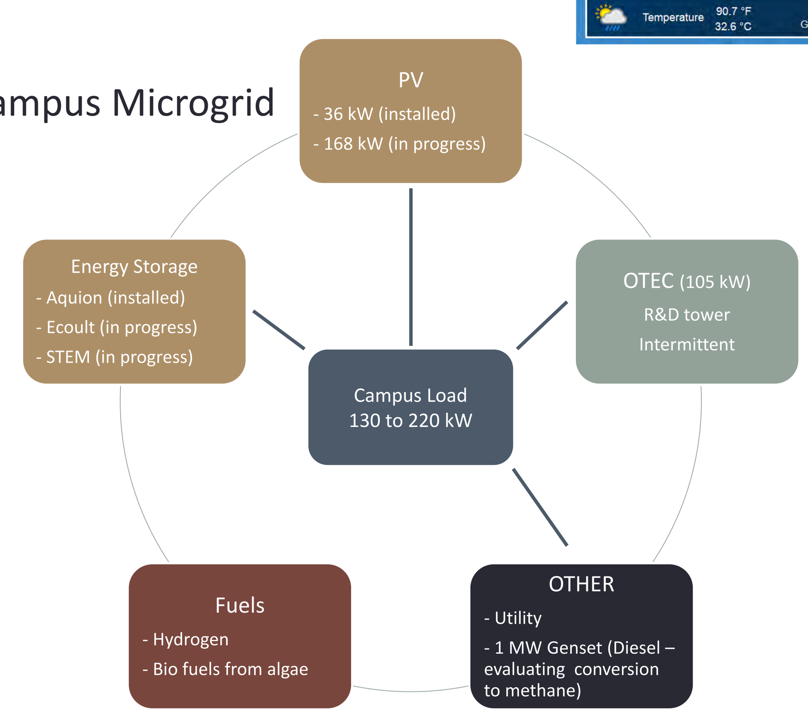
Research Campus Microgrid progress and additions:

- 168 kW PV;
- electrical meters;
- SCADA visualization; and
- energy storage systems.



New NELHA Research Campus microgrid SCADA page

Campus Microgrid



OBJECTIVES OF NELHA TEST BED

- State of Hawaii Goal: 100% Clean Energy by 2045.
- Test Small and large scale ESS systems on Hawaii grid to provide enhancements to resiliency, circuit level frequency, voltage and VAR support, renewable energy dispatching capabilities.
- Test ESS in tropical and marine environments.
- Microgrid development.
- Facilitate development of new clean energy technologies.

GRID SCALE -UET 100KW ESS

UET UniEnergy Technologies

- 100kW/500kWh modular ReFlexTM ESS.
- Advanced vanadium flow technology.
- System will be owned by local utility, Hawaii Electric Light Company.
- Project is in planning and design stage.

Milestones	Date
MOU Execution between NELHA, Ulupono Initiative, Hawaii Electric Light Company	May 8, 2017
Lease Execution	July 27, 2017
Permits and Approvals (except County)	August 31, 2017
Design Drawings and Specifications	September 30, 2017
Installation Drawings and Commissioning Plan	Q4 2017
Complete ESS Commissioning	Q2 2018

Planned ESS location at NELHA Gateway Center

OUR PARTNERS

Hawai'i Electric Light

ulupono INITIATIVE

Sandia National Laboratories

ACKNOWLEDGEMENTS

- **Sandia National Laboratories, Daniel Borneo, ESS Demonstration Program**
- **Ulupono Initiative, Kyle Datta, General Partner**
- **Hawaii Electric Light Company, Jay Ignacio, President**
- **Hawaii Electric Light Company, Bryant Komo, Project Manager**
- **County of Hawaii, Will Rolston, Energy Coordinator**

Special Mahalo to Dr. Imre Gyuk from DOE Office of Electricity without whom the NELHA ESS projects would not be possible.

Exceptional service in the national interest

Sandia National Laboratories

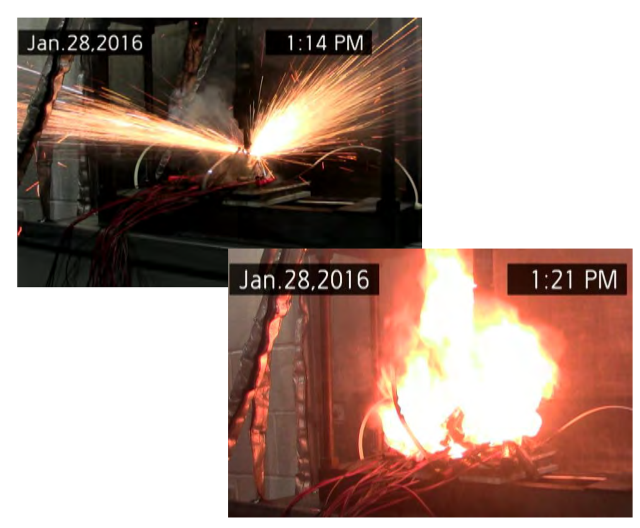
SNL Energy Storage Technology and Systems – Energy Storage Safety
Funded by Dr. Imre Gyuk
U.S. Department of Energy; Office of Electricity; Energy Storage Systems Program

Mitigation Techniques for Failure Propagation

Loraine Torres-Castro, Joshua Lamb, Leigh Anna Steele, Jerry Quintana, Christopher Grosso and June Stanley

Introduction

- Safety of LIB has long focused on the impact and aftermath of a single cell failure.
- Failure of a single cell (inside a pack) may solely have little impact on the safety of the system. However, the thermal and electrical impact on other cells in the pack may be sufficient to cause a cascading runaway effect.
- Work presented here examines the failure propagation behavior of small battery modules constructed with stacked pouch cells and the development of propagation mitigation techniques and strategies.



Methodology

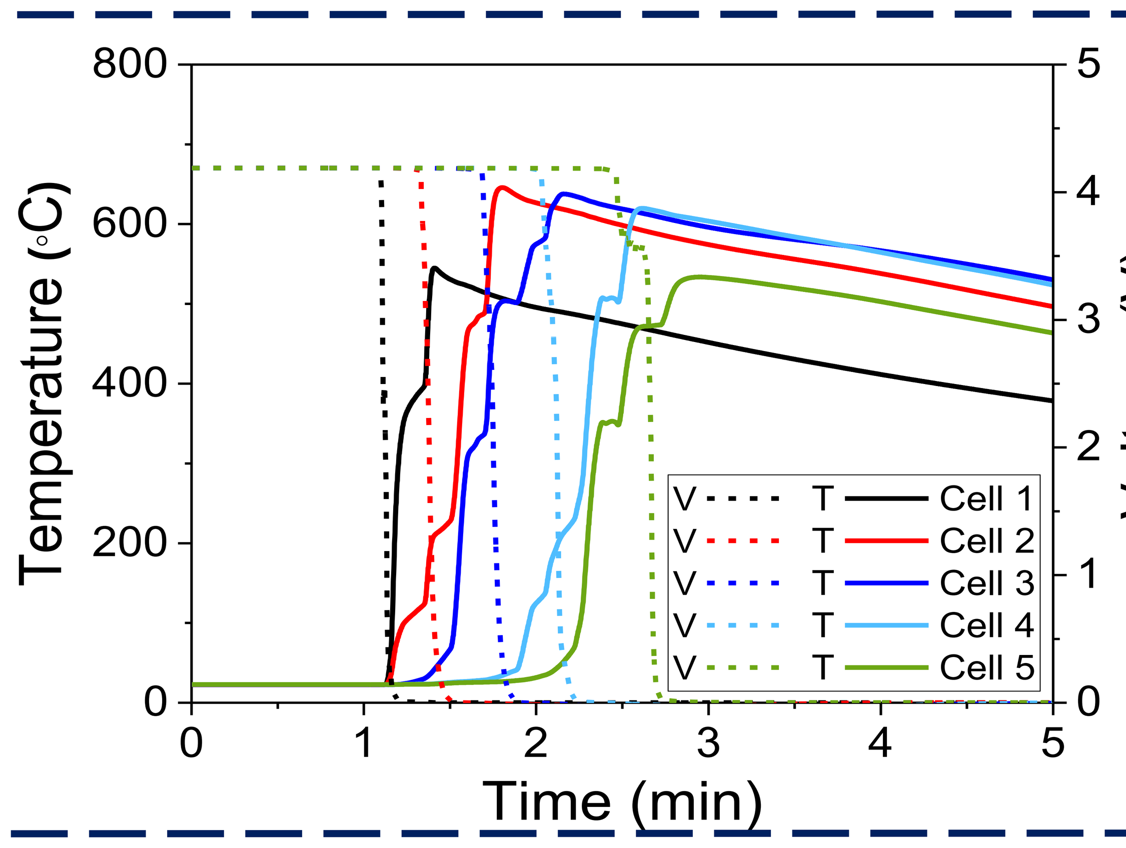
Part I: No Thermal Management

LCO 3Ah cells closely pack together (5 cells) → Pack is setup at 100% SOC → Failure initiated by a mechanical nail penetration

Part II: Passive Thermal Management

LCO 3Ah cells closely pack together with Al or Cu plates between them (5 cells) → Pack is setup at 100% SOC → Failure initiated by a mechanical nail penetration

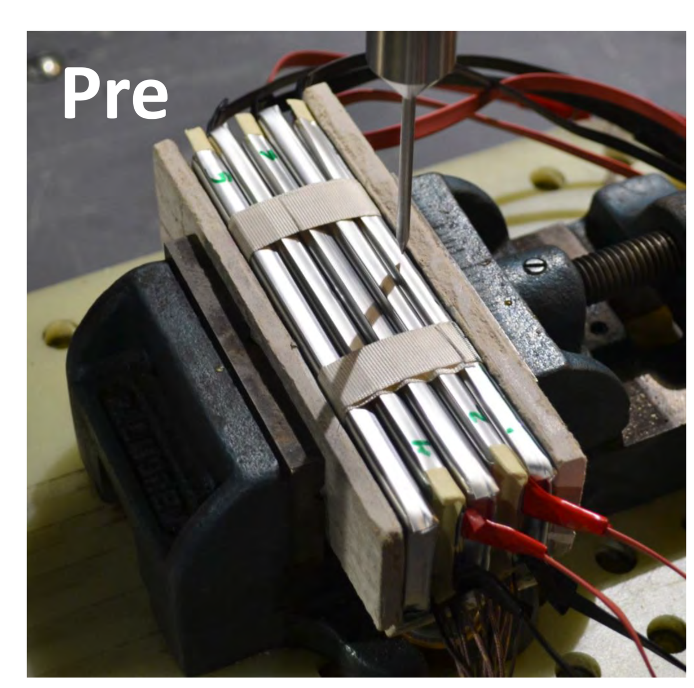
Part I: No Thermal Management

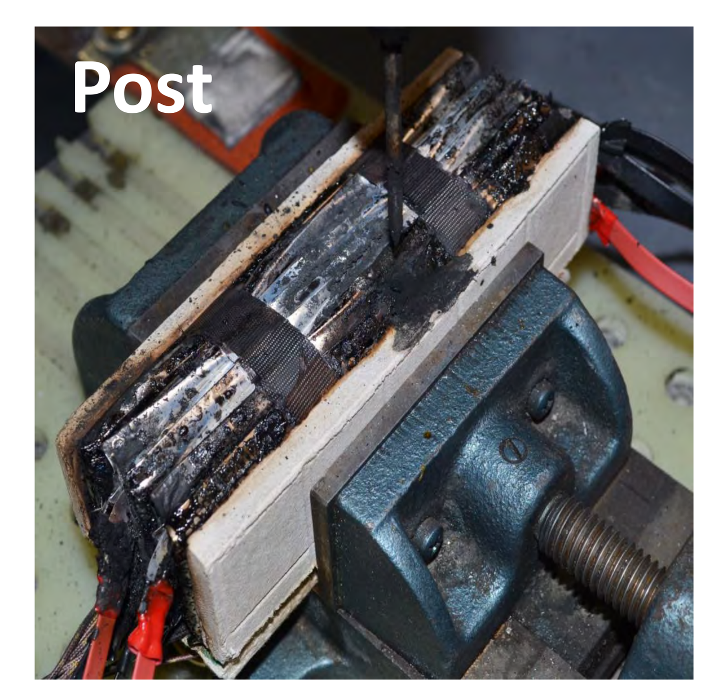


Cell Specifications

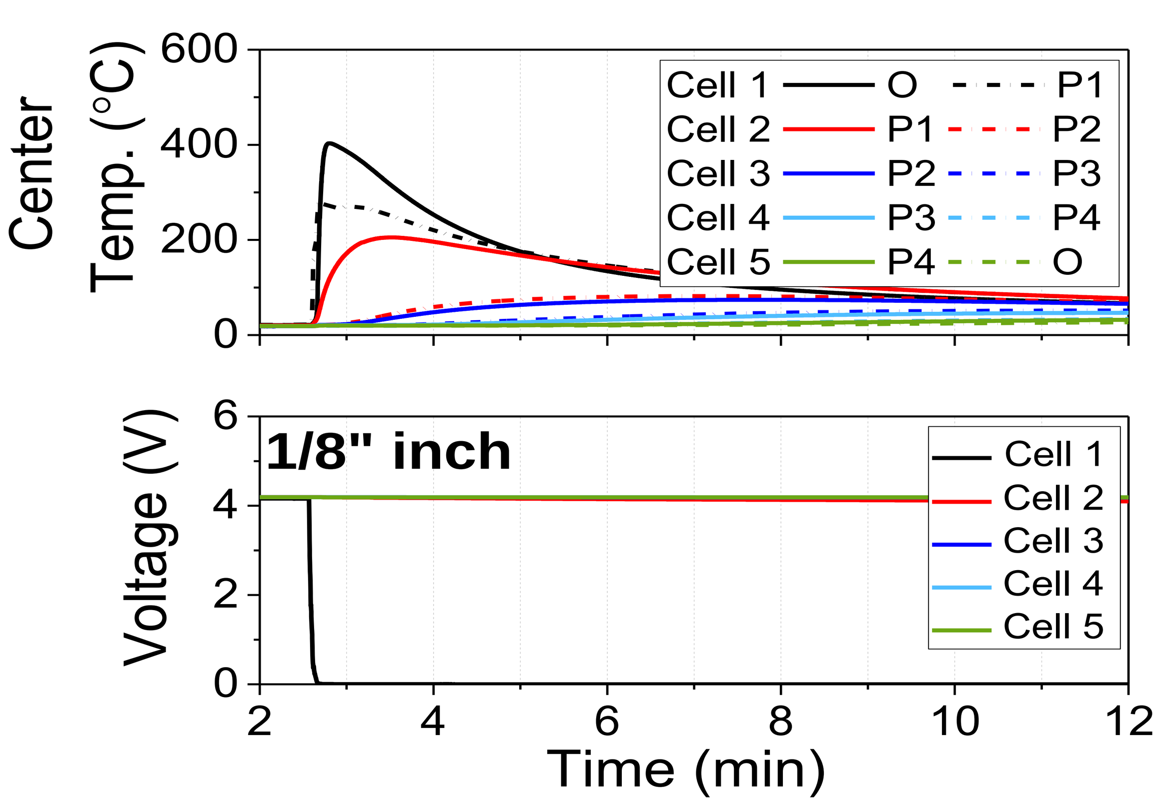
Cathode	LCO
Capacity	3 Ah
Nominal Voltage	3.7 V
Max Discharge Current	10C

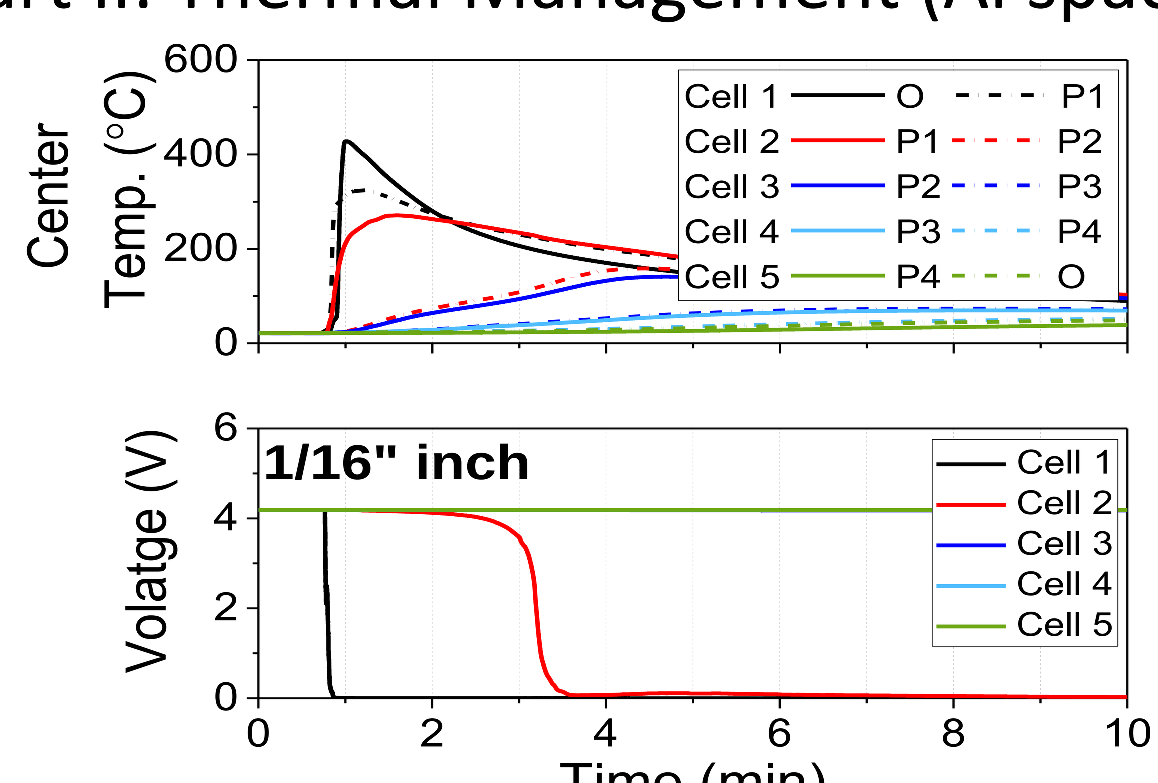
- **Successful initiation at Cell #1.**
- **Propagation to adjacent cells.**
- **Cascading failure to entire battery over 82s.**

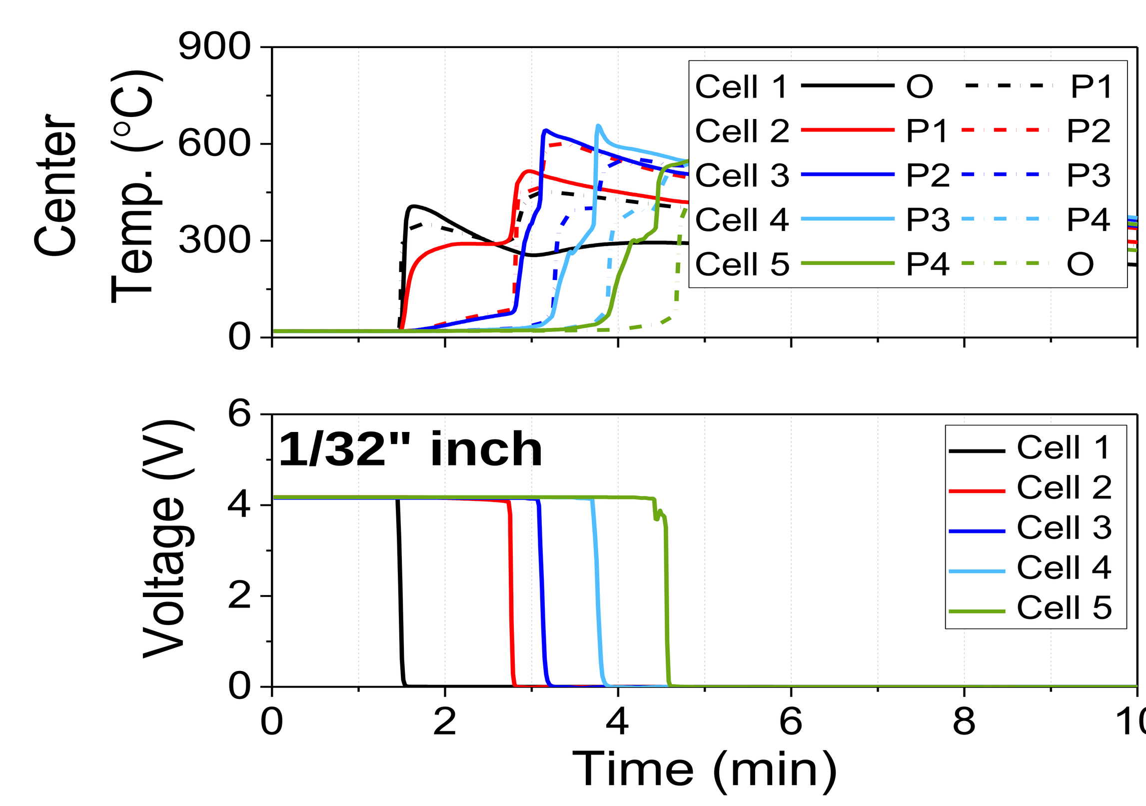




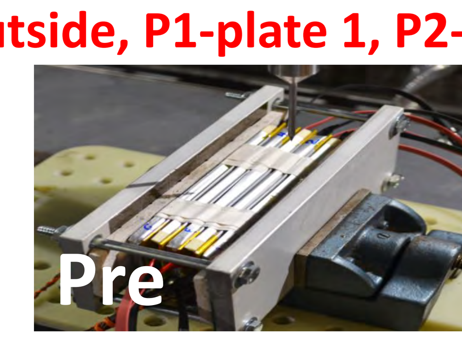
Part II: Thermal Management (Al spacers)*

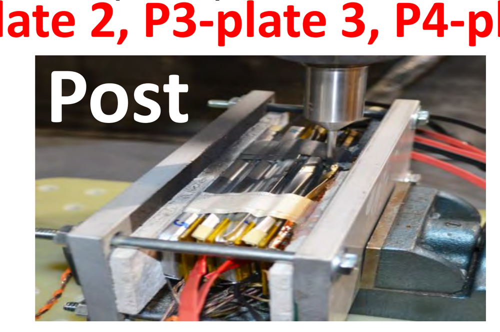


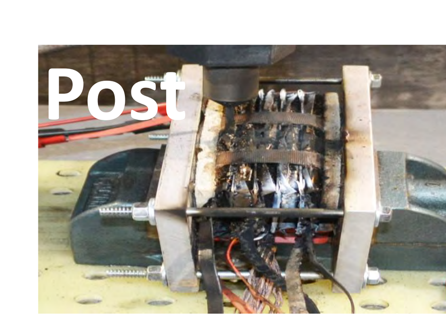




O-outside, P1-plate 1, P2-plate 2, P3-plate 3, P4-plate 4







*These tests were repeated using Cu plates (data not shown).

- **Successful initiation at Cell #1 for all the different tests.**
- **While utilizing 1/8" inch Al or Cu spacers, no propagation was realized.**
- **Limited propagation (from Cell 1 to Cell 2) occurred with 1/16"inch Al and Cu spacers. However, the voltage drop of the pack using Cu spacers was significantly slower.**
- **Cascading failure to the entire battery pack for the thinner material (1/32" inch Cu or Al). Full propagation was realized after 172s and 188s for the packs using Al and Cu spacers, respectively.**

Summary

- As the size and complexity of battery packs increases, single cell failures within a pack become significantly more likely – this work looks at the mechanisms of how a single cell failure might impact a larger battery, as well as how it might be mitigated.
- Unmitigated fully charged pouch cells saw a complete consumption of the packs tested.
- Al and Cu barriers were used as a means of passive thermal management to slow or halt thermal runaway propagation between cells.
- 1/16" plates limited propagation to a single cell, while 1/8" plates arrested it altogether.
- 1/32" plates did not halt propagating battery failure, but did increase the time for full consumption of the pack by 5:1

Funded by Dr. Imre Gyuk through the U.S. Department of Energy; Office of Electricity. A special thanks to the following people for thoughtful discussions, advice, and experiment design: C. Orendorff, H. Barkholtz, S. Ferreira, R. Shurtz and J. Hewson.

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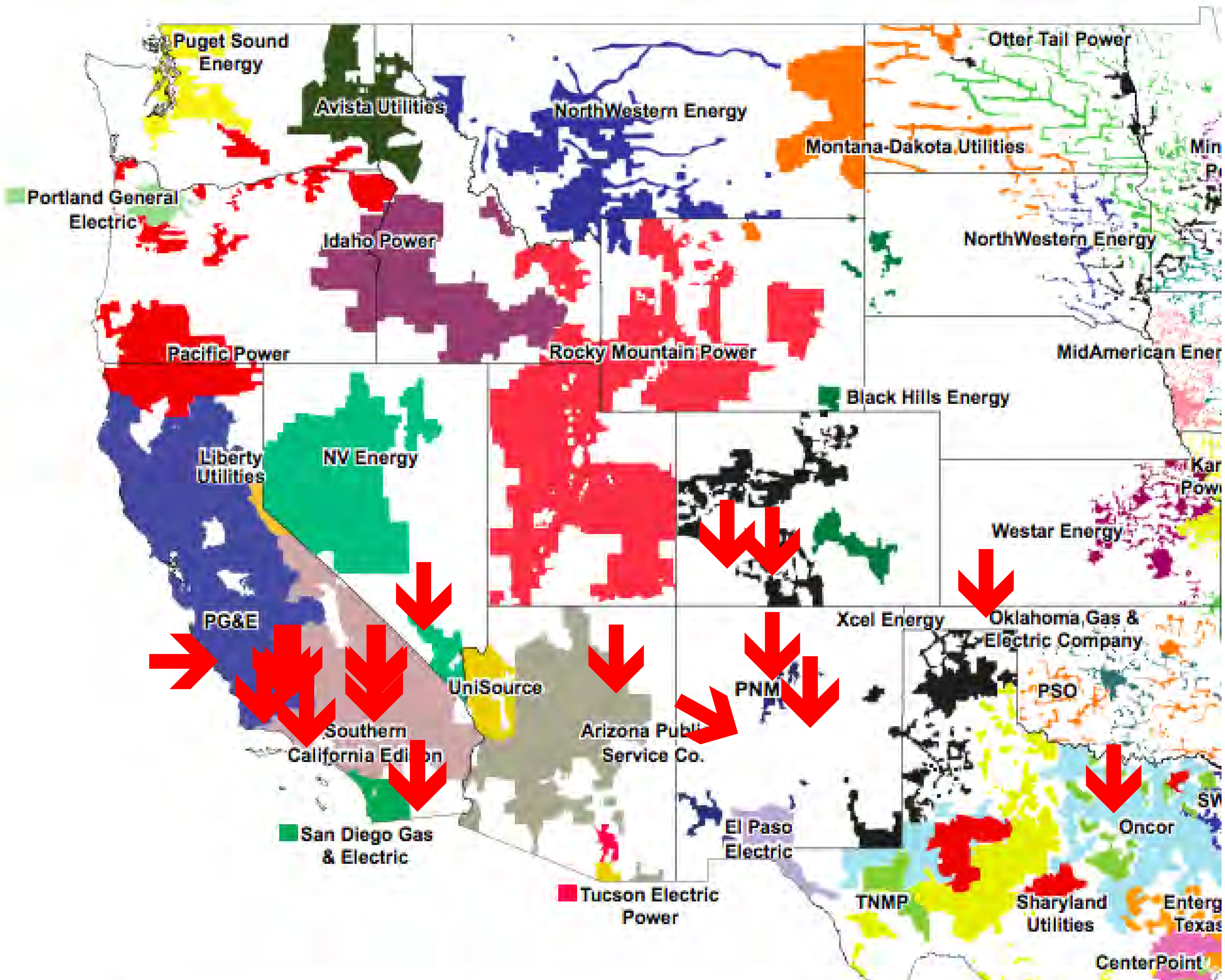
Matt Tafoya, Jaci Hernandez

Vetting Process of the Global Energy Storage Database



Project Objective:

Verify project information for projects featured in the Global Energy Storage Database with a purpose of:

- Correcting project details
- Filling in gaps for undocumented information
- Establishing reliable contacts

Key: Verified Project

Process

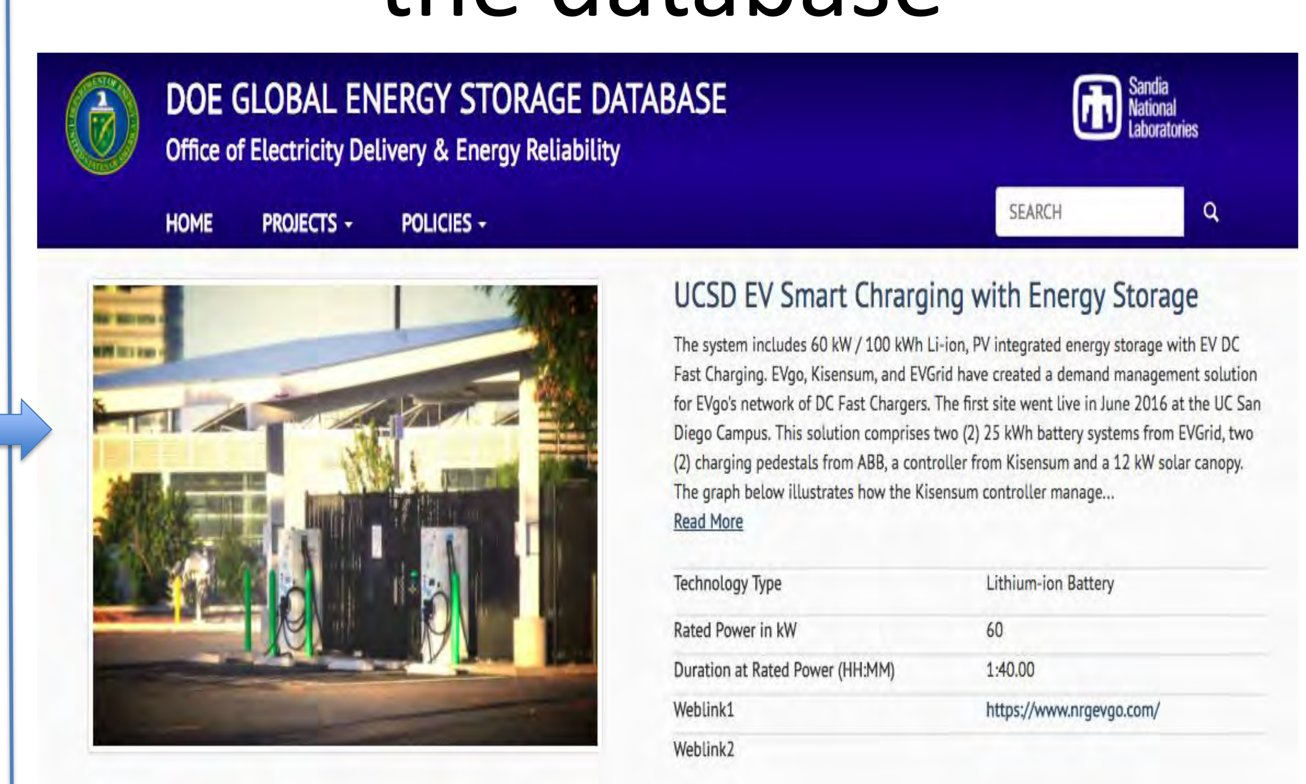
Send information template to project managers

	A	B	C
1	Project Description	Project Name	
2		Project Link	Project Profile Link
3		Technology Type	Lithium-ion Battery
4		Rated Power (kW)	730
5		Duration at Rated Power (HH:MM)	0.5
6		Street Address	9500 Gilman Drive
7		City	La Jolla
8		State/Province	California
9		Zip Code	92093
10		Country	United States
11		Description	730 kW, 1460 kWh SGIP PV Integrated, five off-campus sites. Future planned projects
12		Web Link	http://cer.ucsd.edu/_files/energy-storage-ppt
13	Project Status	Project Status	Project Status
14		Announcement Date (YYYY-MM-DD)	42109
15		Construction Date(YYYY-MM-DD)	
16		Commissioning Date (YYYY-MM-DD)	
17		Decommissioning Date (YYYY-MM-DD)	
18		Multiple System (Yes/No)	Multiple System (Yes/No)
19	Siting	ISO/RTO	CAISO
20		Utility	
21		Utility Type	
22		Grid Interconnection	
23		Paired Grid Resource	
24		Ownership Model	Third-Party-Owned

Document updates made by project managers

	A	B	C
1	Project Description	Project Name	
2		Project Link	Project Profile Link
3		Technology Type	Lithium-ion Battery
4		Rated Power (kW)	2500
5		Duration at Rated Power (HH:MM)	2
6		Street Address	9500 Gilman Drive
7		City	La Jolla
8		State/Province	California
9		Zip Code	92093
10		Country	United States
11		Description	2,500kW, 5,000 kWh SGIP PV Integrated, five off-campus sites. Future planned projects
12		Web Link	http://cer.ucsd.edu/_files/energy-storage-ppt
13	Project Status	Project Status	Operational
14		Announcement Date (YYYY-MM-DD)	11/1/15
15		Construction Date(YYYY-MM-DD)	
16		Commissioning Date (YYYY-MM-DD)	
17		Decommissioning Date (YYYY-MM-DD)	
18		Multiple System (Yes/No)	No
19	Siting	ISO/RTO	CAISO
20		Utility	
21		Utility Type	
22		Grid Interconnection	
23		Paired Grid Resource	
24		Ownership Model	Owner

Update information on the database



Thank you Dr. Imre Gyuk, DOE/OE Energy Storage Program Manager, for funding in partnership with the Clean Energy States Alliance (CESA).

Value of High Power, Short Duration Energy Storage

Helix Power

1 The issue

Helix Power Hardware Manages Utility Scale Power Bursts

Huge Problem: High Power Bursts	Short duration high power (megawatt+) power bursts and fluctuations must be managed
Current "Solutions" are Inefficient	Waste energy, increase emissions, raise costs, and reduce system resiliency
Helix Solution	Substantially more efficient by design leading to lower costs, emissions, energy use and improved power equipment life

2 Storage Segments

Big Markets exist!

Grid Scale Storage Market Segmentation

Application Class	1 Power Management	2 Energy Balancing	3 Load Shifting / Shaving
Storage Duration	90-300 Seconds	15 Minutes	2-10 Hours
Applications	Metro regenerative braking Mining and industry • Renewables integration	• Grid frequency regulation • Frequency response	• Arbitrage renewable energy
Expected life	20 years	20 years	10 years
Cyclic life required	1,000,000 cycles • 100 – 150 cycles/day	100,000 cycles • 10-15 cycles/day	10,000 cycles • 1-2 cycles/day
Competition	Flywheels have lowest lifetime cost and highest cyclic life	Batteries and flywheels are half the cost of new generators	Low cost generators are currently less expensive than storage

Initial Helix Application

Power burst management specs are very different from bulk storage specs
Universal 1MW – 90 sec flywheel platform is common for all power burst applications

3 Throughput Value

Big savings exist

Stored Energy Throughput Cost

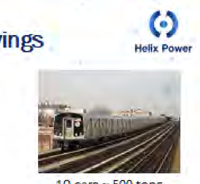
	Power Management	Balancing	Load shift
Technology	Flywheel	Flywheel	Battery
C-rate	40C	4C	0.2C
Nameplate Power KW	1,000	100	1,000
Nameplate energy kWh	25	25	4,000
Depth of discharge DoD %	100%	100%	50%
Equivalent full cycles	1,000,000	100,000	10,000
Cycles per day	125	12	2
life -- years	22	23	14
Lifetime energy throughput MWh	25,000,000	2,500,000	40,000,000
Cost of 1 nameplate unit $	1,000,000	300,000	1,333,000
Cost per moved kWh $/kWh	**0.040**	**0.120**	**0.067**

4 Launch Application

Significant interest by NYC Transit

Metro Transit Small Bits Aggregate into Large Savings

- New York MTA Case Study:*
  - Largest consumer of electricity in NYC
  - Estimates show savings up to 50% of energy used for train acceleration
  - MTA could save up to 1TWh/year of electricity by recycling braking energy (energy cost savings $100M+ annually)
  - Initial estimates indicate approximately 350 flywheels will be needed for full build-out of the MTA system
  - CO_2 Avoided: 350,000 tons/year at full build-out



10 cars ~ 500 tons

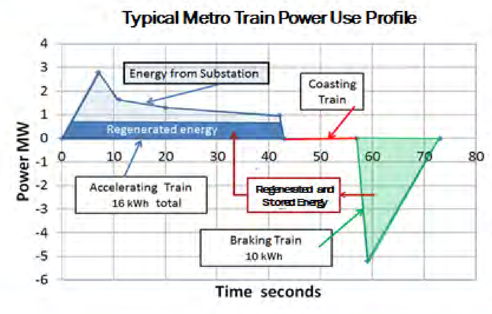
Braking Resistors

*Source: MTA Reports

5 Regen Braking

Up to 50% energy savings are possible

What is Regenerative Braking?



- Regenerative braking is used in hybrid and electric cars
- Regenerative braking can recycle 50% of a train's energy
- Today, In NY City, braking energy is not reused and is dumped as heat

6 System Requirements

Watch the Heat !!!

Helix Platform Specification

Platform Spec	Effect for Metro System
90 Sec Charge - Discharge @ 1MW	Matches train acceleration and braking times
20 year operating life	Matches subway project time frame
1,000,000+ full charge/discharge cycles	Meets High Frequency Train stop schedule
Full Power – Continuous Operation	Operates 3.5 hours non-stop during rush hour
600 Volt DC Interface	Fits requirements of metro subway line voltage

Power burst management specification is very different from bulk storage
Universal 1MW – 90 sec flywheel platform is common for all Power Burst applications

7 Heat Resistant Motor Patent

Component testing started

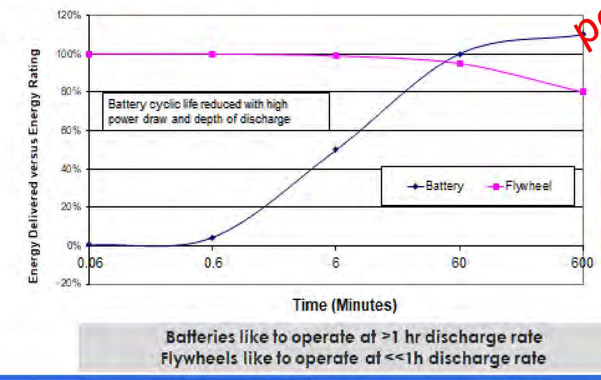
Competitive Advantage Driven by Innovation

- Filed Breakthrough Patent Application
- Application describes innovative magnetic components functioning in a high power motor
- Advances in thermal management of magnets and rotor enables:
  - Significantly higher power motors
  - Continuous high power operation

Helix method controls heat buildup and solves fundamental issues blocking path to economic use of high power flywheels

8 Flywheels vs. Batteries

Flywheels offer pomising solution



Curves are using typical or generic LA battery data from for illustration purposes.

Other chemistries will have other curves

Batteries like to operate at >1 hr discharge rate
Flywheels like to operate at <<1h discharge rate

9 Value Streams

Benefits and value streams

- Primary value stream: 30%-50% less energy bought
- Unload Substation, defer substation upgrades
- Bolster 3rd rail power on long interstation gaps
- Provide virtual generator in cities
- Allows train company to resell power at higher price
- Potential homeland security support
- Less heating of subway tunnels
- Small footprint

Thank You!

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NNSA National Nuclear Security Administration

Matthew Lazarewicz, President, Helix Power lazarewicz@helixpower.com
DOE Peer Review Oct 9-10, 2017
EESAT 2017 Oct 11-13. 2017
San Diego CA

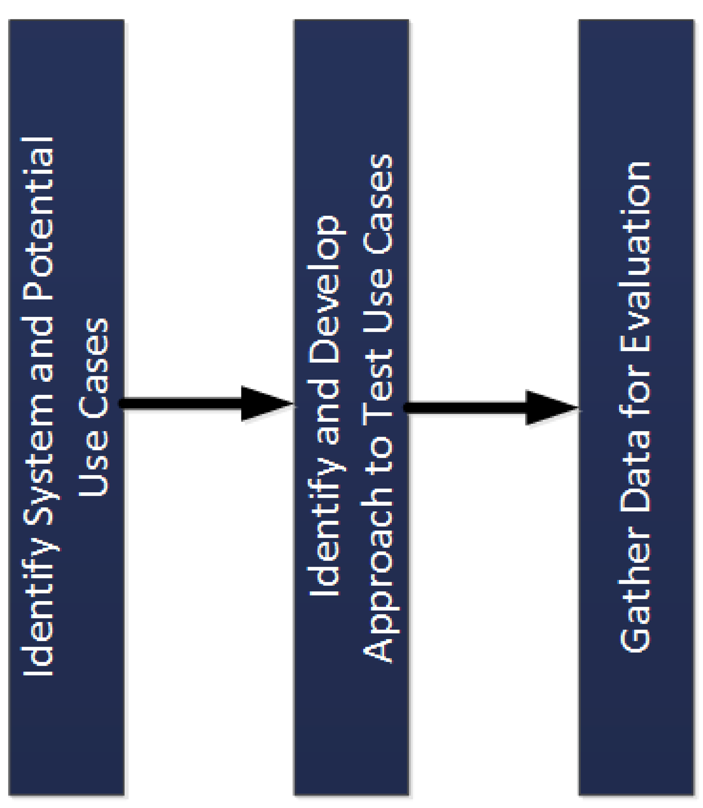
Energy Storage Deployment and Evaluation with the Electric Power Board (EPB)

Michael Starke[1], Jignesh Patel[1], Andrew Herron[1], Jim Glass[2], Sharon Russell[2],
[1]Oak Ridge National Laboratory, Oak Ridge, TN USA 37831; [2]Electric Power Board, Chattanooga, TN USA 37404;

Introduction

- Project goal is to deploy and economically evaluate a 100kW/400kWh UET flow battery energy storage system with the Electric Power Board (EPB) of Chattanooga
- EPB is a municipally-owned distribution utility serving 175,000 homes and businesses in Chattanooga, TN
- EPB has installed 1.3MW of PV, which was commissioned in summer 2017

Approach

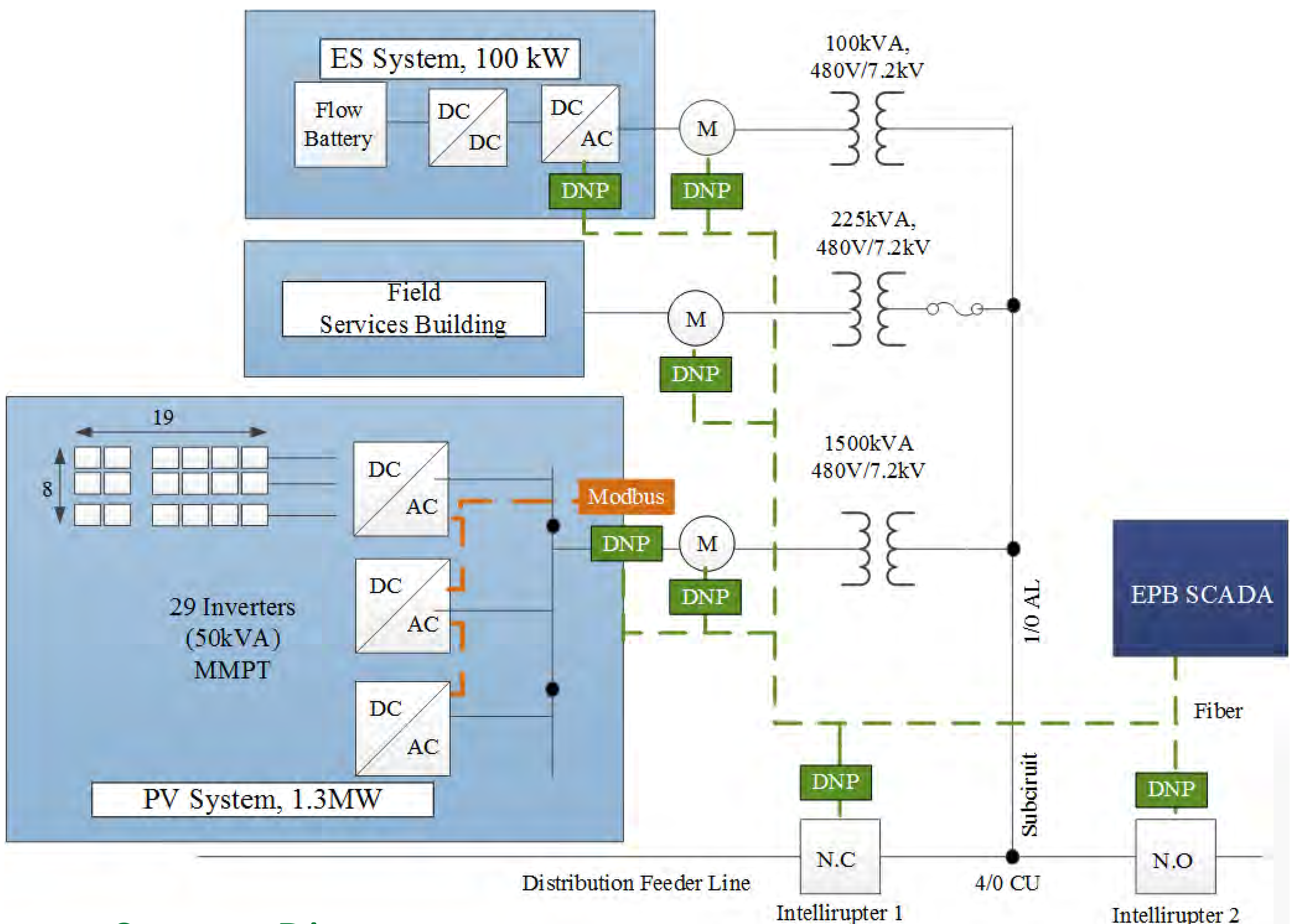


Methodology

- The objective is to demonstrate economically viability via data collection and evaluation.
- Use cases must be defined and tested under common protocol.
- Methods to implement the use cases through EPB system must be identified and developed.
- Data is needed to demonstrate use cases.

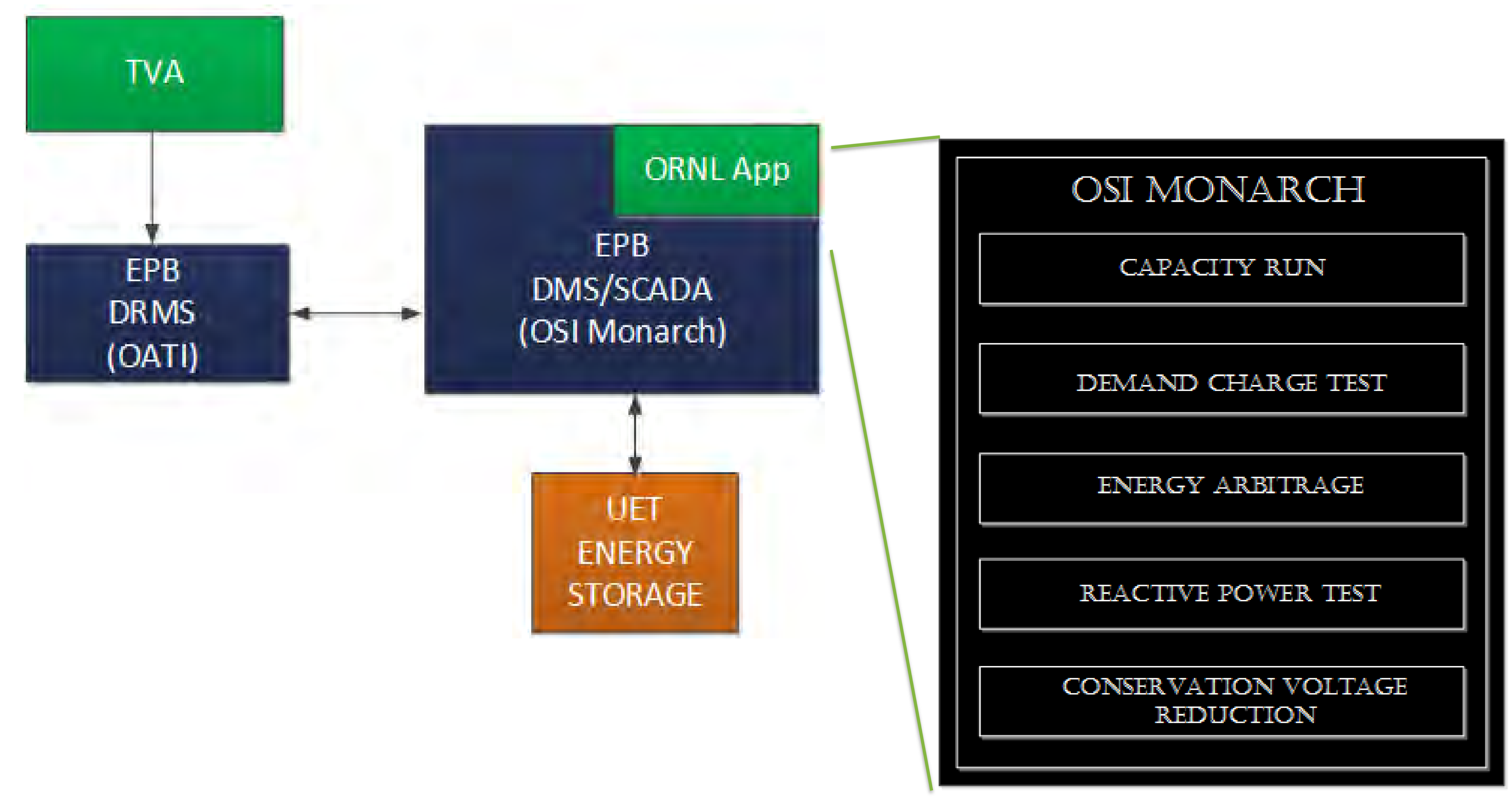
Results

- EPB System examined for use cases and several were found:
  - Demand Charge Reduction
  - Energy Arbitrage
  - Reactive Power and Voltage Support
  - Microgrid Field Services Building
- Others still being investigated:
  - TVA transmission services and Demand Response Program



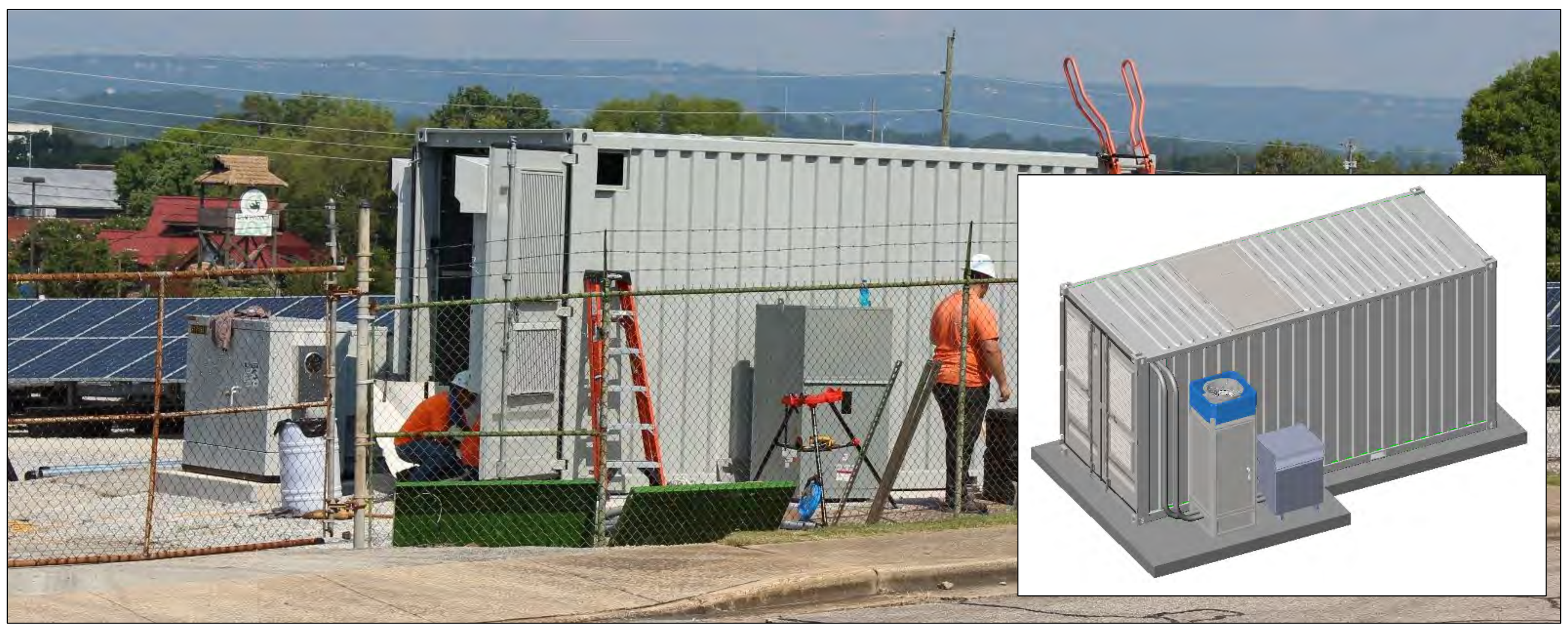
System Diagrams

- Approach to Integration Identified:
  - Directly code applications into EPB OSI Monarch System



System Interfaces

- Applications are being programmed to match PNNL-20220.
- Results will be compared with Sandia National Laboratory data collection on similar testing of energy storage system.



System Commissioned: Sep. 22nd, 2017

- System currently undergoing battery conditioning and remote testing by UET.
- Expected to initiate interface and testing in late October.

Future Work

- Finish Integrating protocols into EPB SCADA application.
- Test protocols functionality on EPB SCADA test harness
- Run Energy storage using test protocols and collect data
- Run Energy storage on optimized use cases
- Evaluate the data and examine Final Economic Potential of System

Acknowledgements

- This work has been funded by Imre Gyuk at the Department of Energy, Office of Electricity, Energy Storage Program
- Partners: Sandia National Laboratory, Pacific Northwest National Laboratory, and UET

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Reliable High-Performance Gate Oxides for Wide Band Gap Devices

Peter T. Dickens,[1] Elizabeth A. Paisley,[1] Sean W. Smith,[1] Michael Brumbach,[1] Adam Morgan,[1,2] Christopher T. Shelton,[2] Brendan Gunning,[1] Andrew Allerman,[1] Jon-Paul Maria,[2] Stanley Atcitty,[1] and Jon Ihlefeld,[1,3]
[1] Sandia National Laboratories, [2] North Carolina State University, [3] University of Virginia
Contact Information: pdicke@sandia.gov or satcitt@sandia.gov

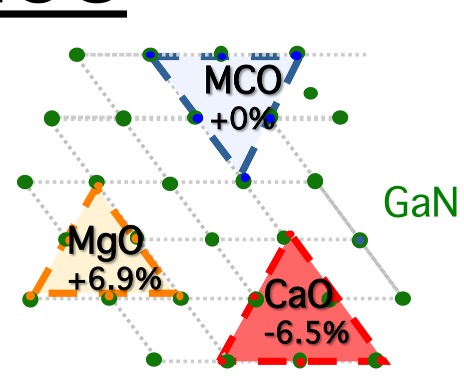
Motivation

- Power conversion systems are the enabling technology for modern power electronics.
- The metal-oxide-semiconductor field effect transistor (MOSFET) is the heart of power conversion systems.
- Wide bandgap semiconductor devices provide the opportunity to improve the performance through access to higher voltages, temperatures, and switching speeds.
- **However, normally-off GaN MOSFETs are currently unavailable due to issues with oxide layer reliability, driven by interface chemical and structural instability.**

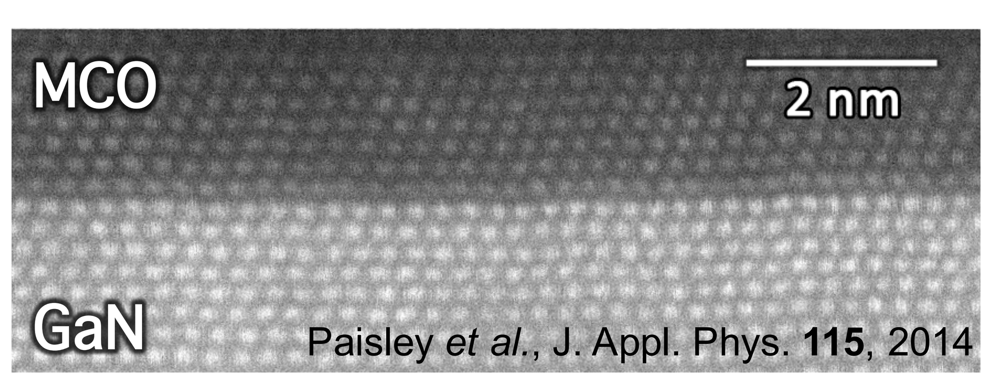
In this project new oxide layers, $Mg_xCa_{1-x}O$, are being developed which are designed to be chemically, structurally, and electrically compatible with III-V.

Approach: MCO

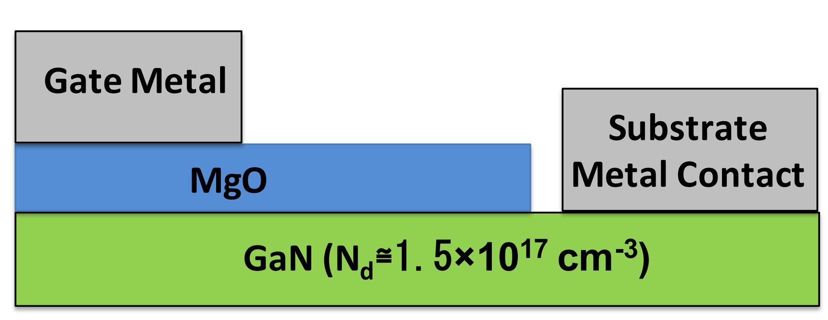
- **$Mg_xCa_{1-x}O$ (MCO) is an alloy of MgO and CaO, which have lattice constants that can match directly to GaN or SiC.**
- For example, solid solutions of 50% MgO and 50% CaO atomically align with GaN and show no dislocations due to lattice-mismatch.



HR-TEM image of oxide | semiconductor interface



Device design:



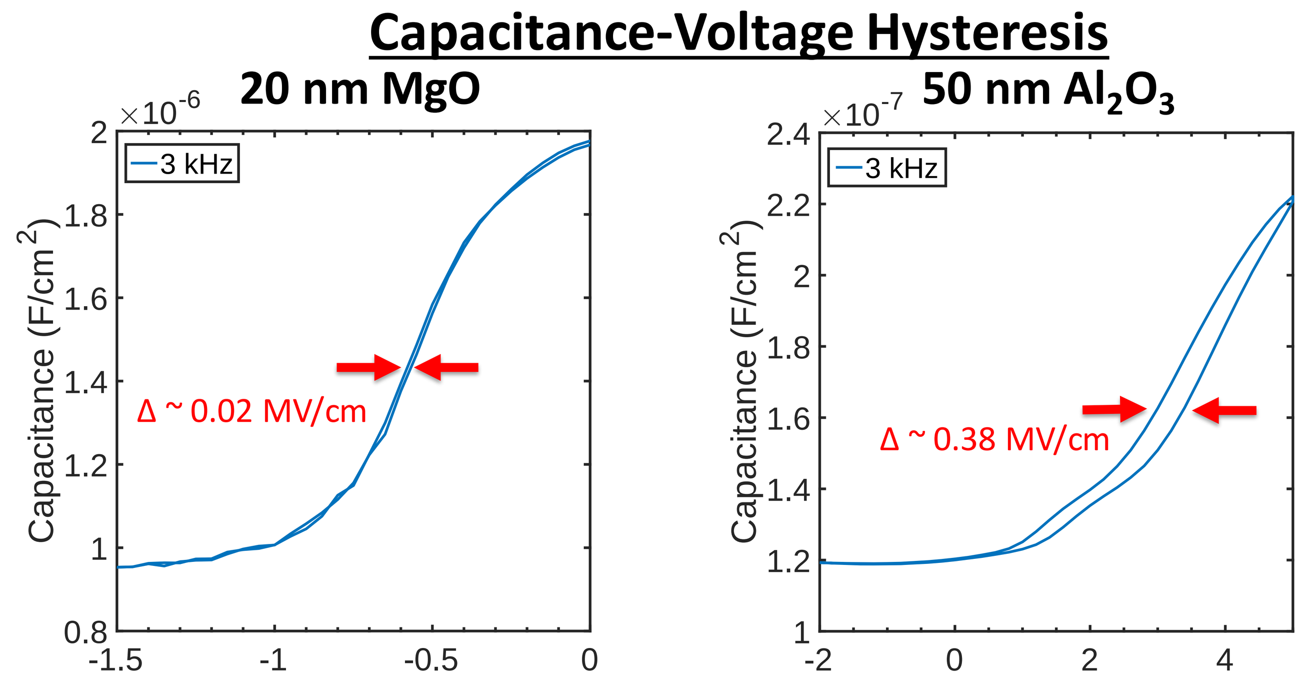
FY17 Activities

1. Measure electrical performance of metal-oxide-semiconductor (MOS) capacitors made with MgO and compare performance to conventional oxide layers (Al_2O_3).
   - Goal: Characterize
     - A. Oxide trapped charge density
     - B. Frequency dispersion
     - C. Leakage current across MOS interface
2. Improve oxide electrical performance by elimination of interface traps through tuning of processing and growth techniques.

A. Oxide Trapped Charge

- Trapped charge is caused by slow trapping states, resulting in hysteresis of the C-V curve.
- MgO/GaN demonstrates 19x improvement over Al_2O_3

Capacitance-Voltage Hysteresis

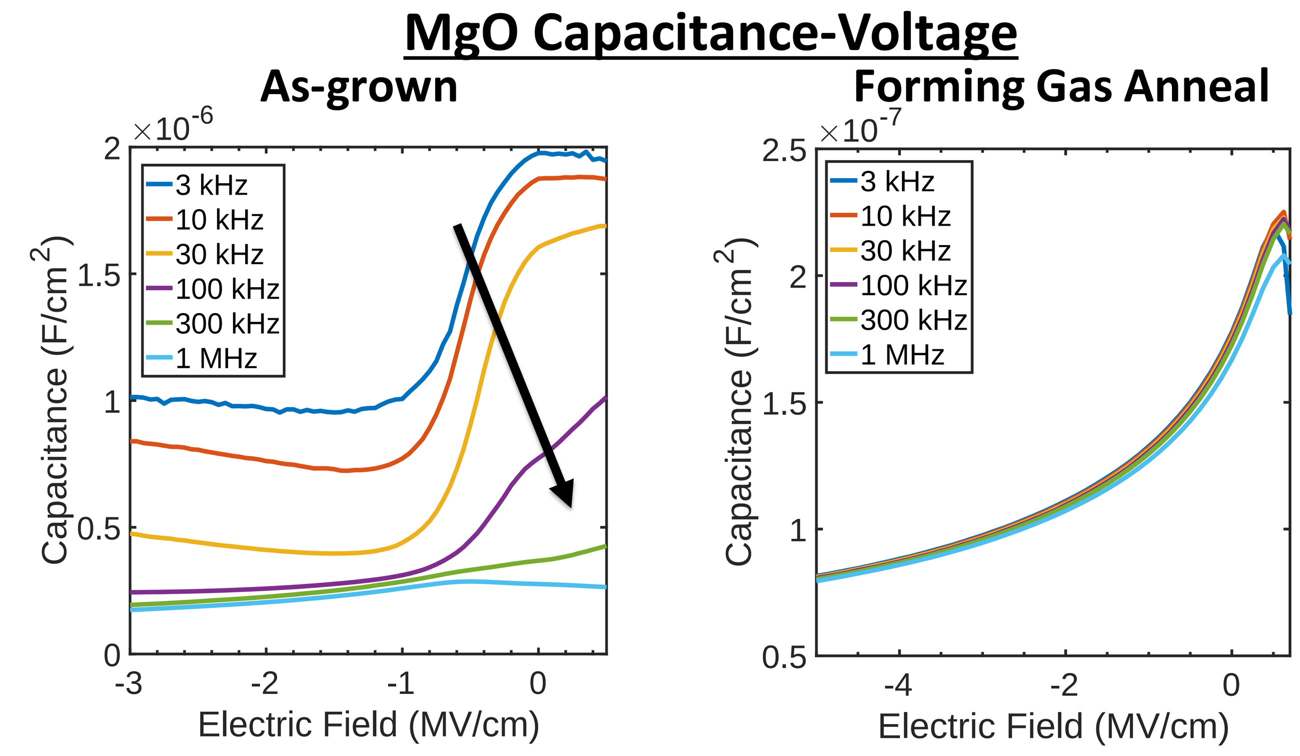


➔ Fewer defects present in MgO

B. Frequency Dispersion

- Frequency dispersion in the C-V under accumulation curve results from defects at the oxide/GaN interface.
- As-grown samples demonstrated large frequency dispersion.
- Annealing is commonly used to eliminate defect states post growth. A forming gas anneal eliminated dispersion and decreased measured interface states (D_{it}).

MgO Capacitance-Voltage

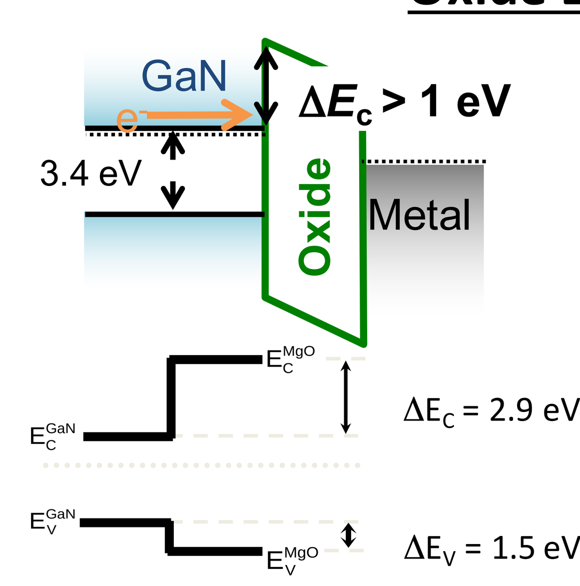


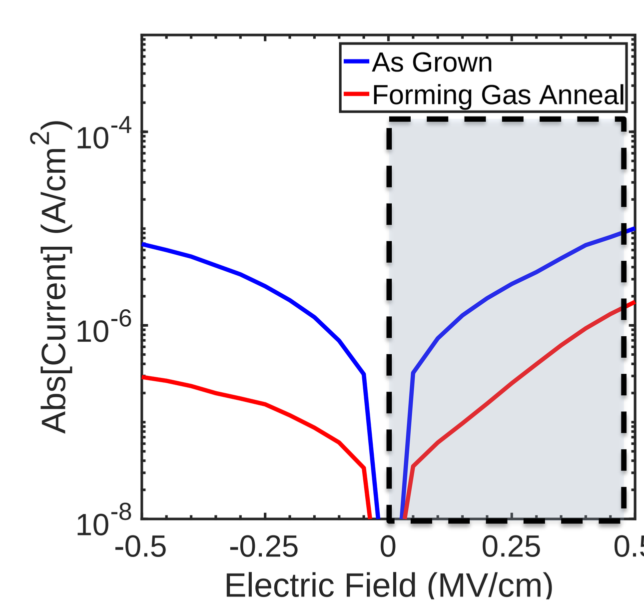
➔ Annealed MgO shows lower interface state density

C. Leakage Current

- Lower device leakage current enables improved reliability and efficiency.
- At +0.5 MV/cm, annealed film exhibits 1.75 μA/cm² which is a 6x improvement over the as-grown sample.

Oxide Leakage Current





➔ Fewer defects present in MgO

FY17 Publications and Impact

- Has demonstrated improved performance of MgO gate oxide over alumina.
- Research presented at 2 conferences (one invited, one contributed) and 3 invited colloquia
- Christopher T. Shelton, Isaac Bryan, Elizabeth A Paisley, Edward Sachet, Jon F. Ihlefeld, Nick Lavrick, Ramon Collazo, Zlatko Sitar, Jon-Paul Maria. "Step-free GaN surfaces grown by confined-area-metal-organic vapor phase epitaxy." Applied Physics Letters, accepted for publication September 2017.
- 1 additional publication in submission

FY18 Goals and Milestones

- D_{it} study for lattice matched MgO-CaO on GaN and SiC
- High temperature device testing
- Prepare lattice matched alloys on SiC and pursue device development with industrial partner

We gratefully acknowledge Dr. Imre Gyuk and the DOE Office of Electricity Energy Storage Program for funding this work

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Reliability Study of Vanadium Redox Flow Batteries by Superior Stable DHE

Qian Huang [a], Bin Li [a], David Reed [a], Chaojie Song [b], Alison Platt [b], Khalid Fatih [b], Zhengming Jiang [b], Christina Bock [b], Darren Jang [b]

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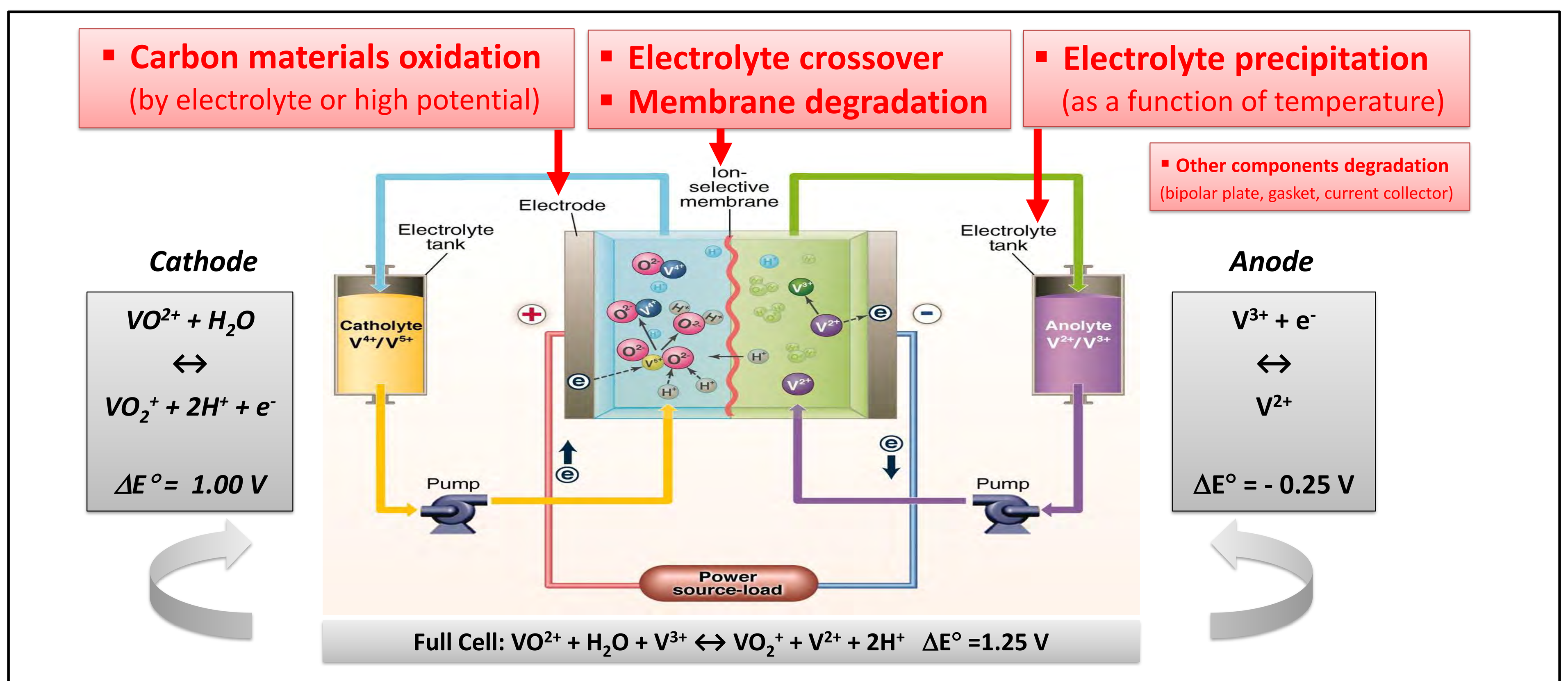
Introduction: To fundamentally understand the reliability and degradation mechanism is becoming a critical topic for large scaled energy storage systems in smart grid integration application. As a highly promising candidate for stationary energy storage, redox flow batteries (RFB) are mostly studied in a full cell with simply monitoring the cell voltage and current in varied operation conditions. Studies indicate that contributions from individual electrodes are hard to be separated especially for long-term cycling testing due to the lack of a stable reference electrode in RFB, however, it is in high demand and vital for the mechanistic investigation of RFB reliability.



Vanadium Redox Flow Battery (VRFB) Degradation Mechanisms

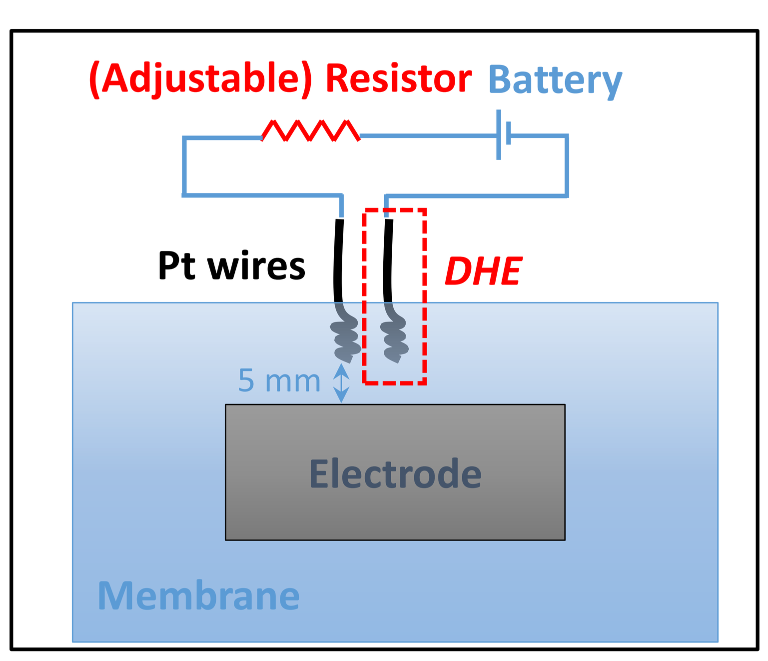
Objectives and Approaches:

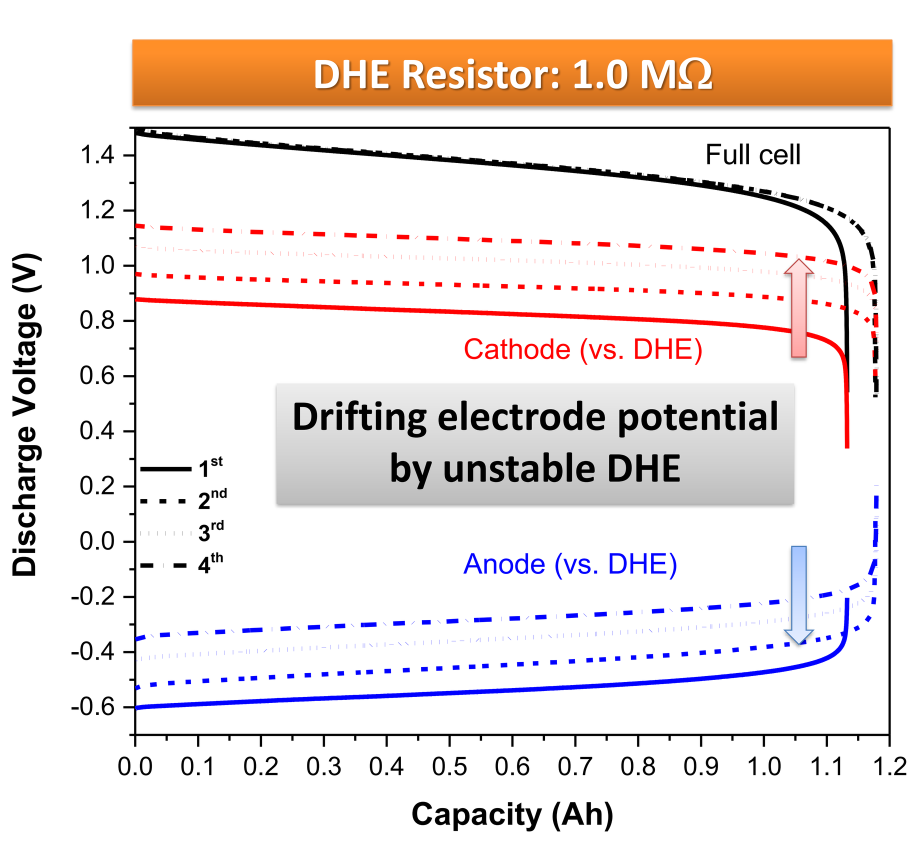
- Stable reference electrode development to decouple the cathode and anode during long-term testing of VRFB;
- Accelerated stressor lifetime testing (ASLT) protocol development for VRFB;
- Fundamental understanding of degradation mechanism of VRFB component and system.

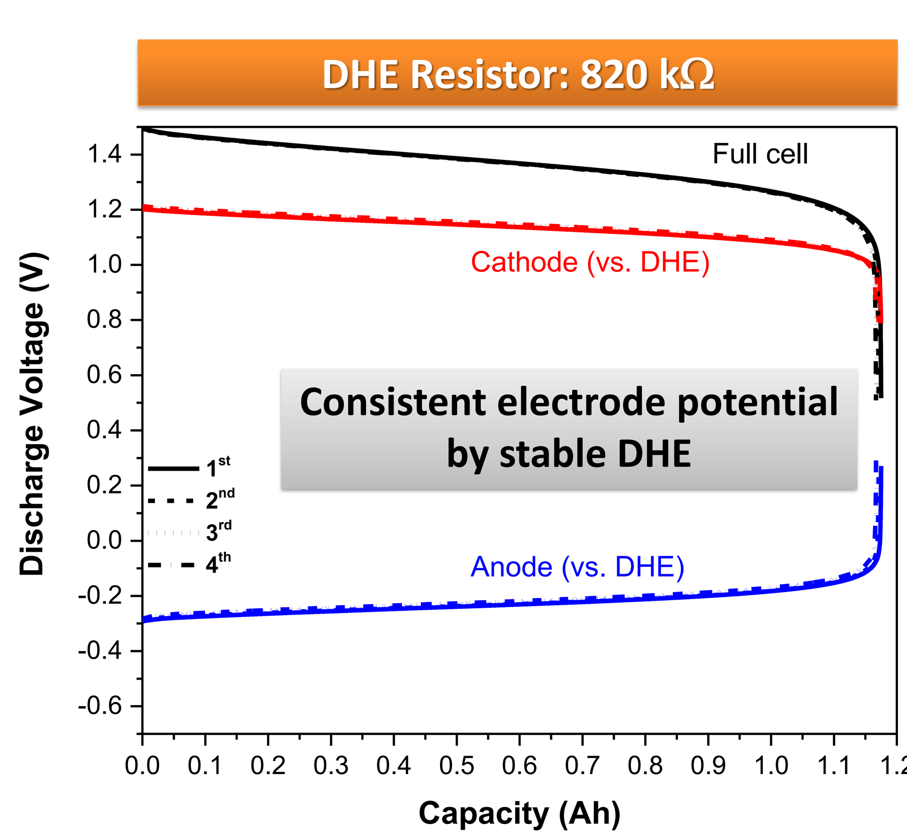
Results and Discussion:

a) Dynamic hydrogen electrode (DHE) based reference electrode development

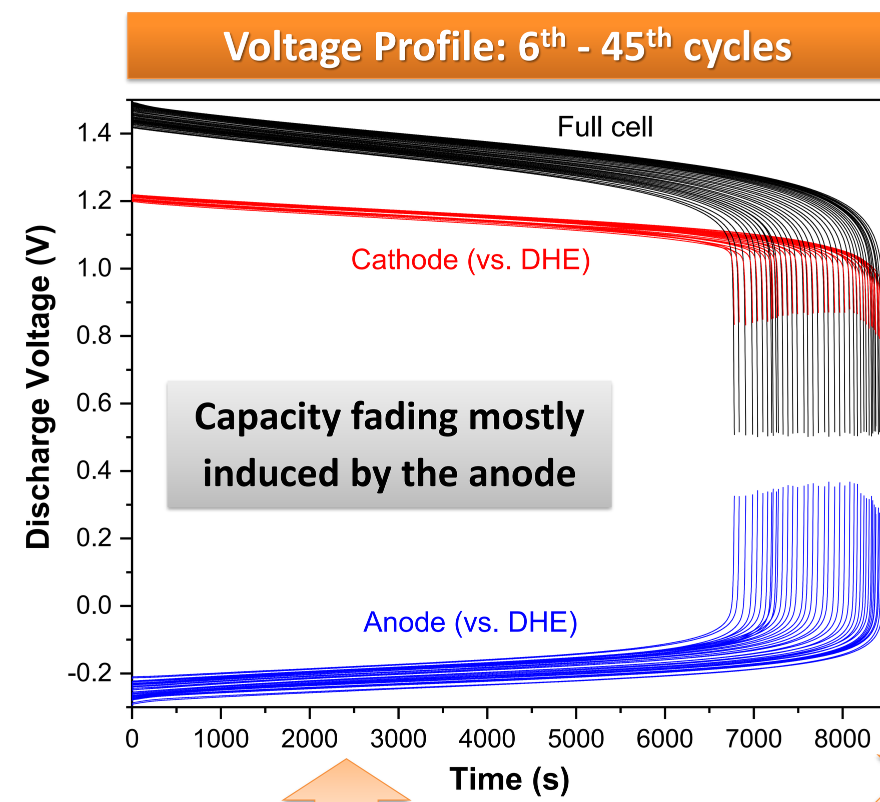
- Optimized design with adjustable resistor
- Sandwich between laminated membranes
- Validated *resistor effect* on the stability of DHE

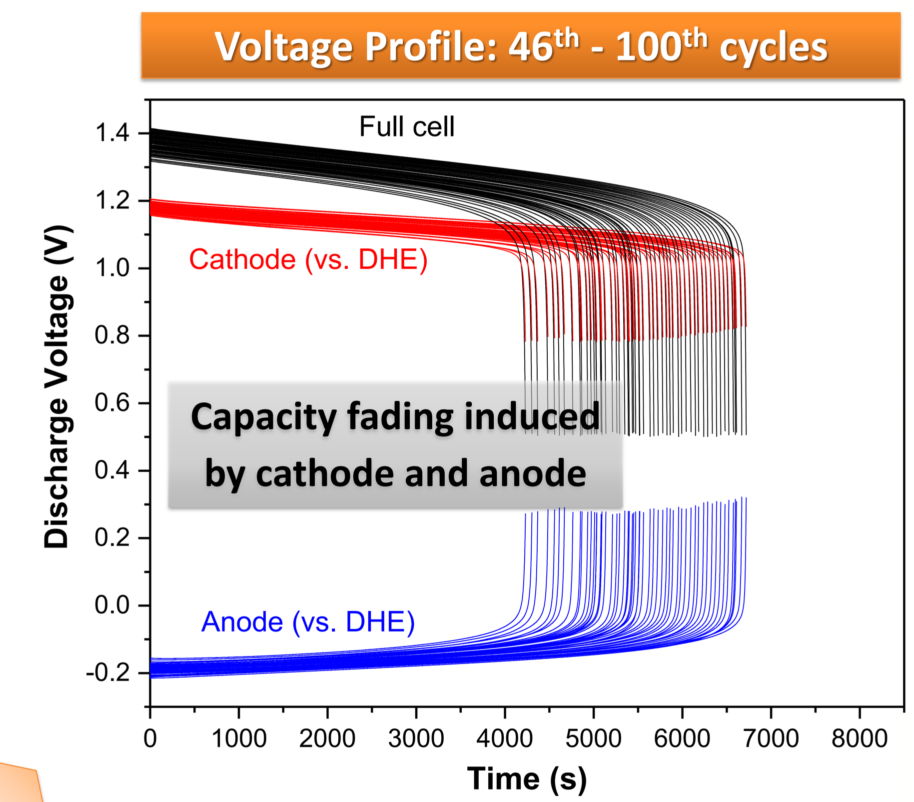


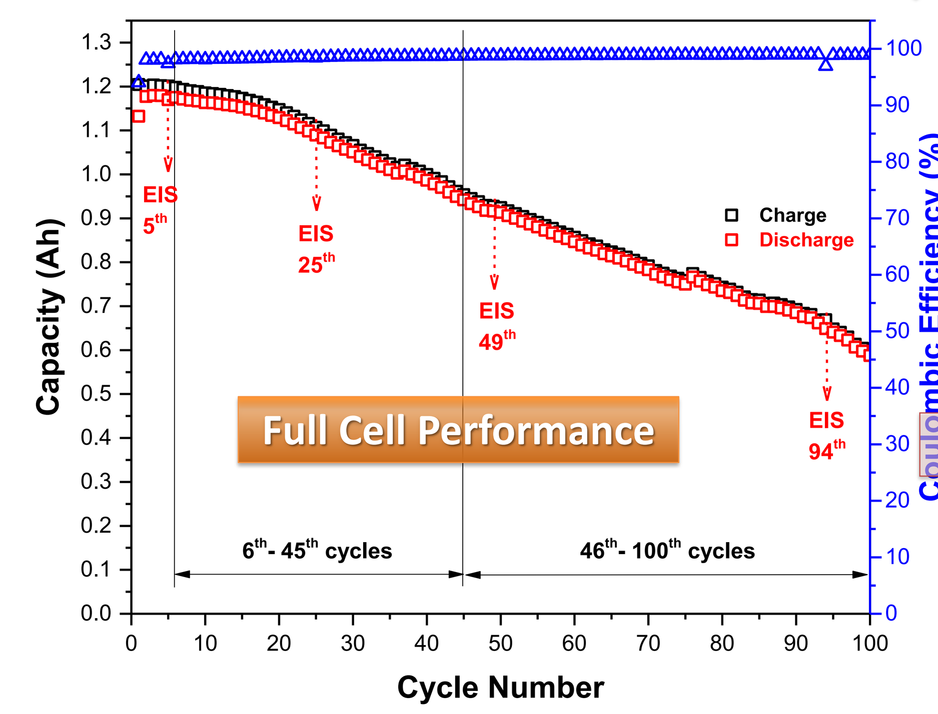


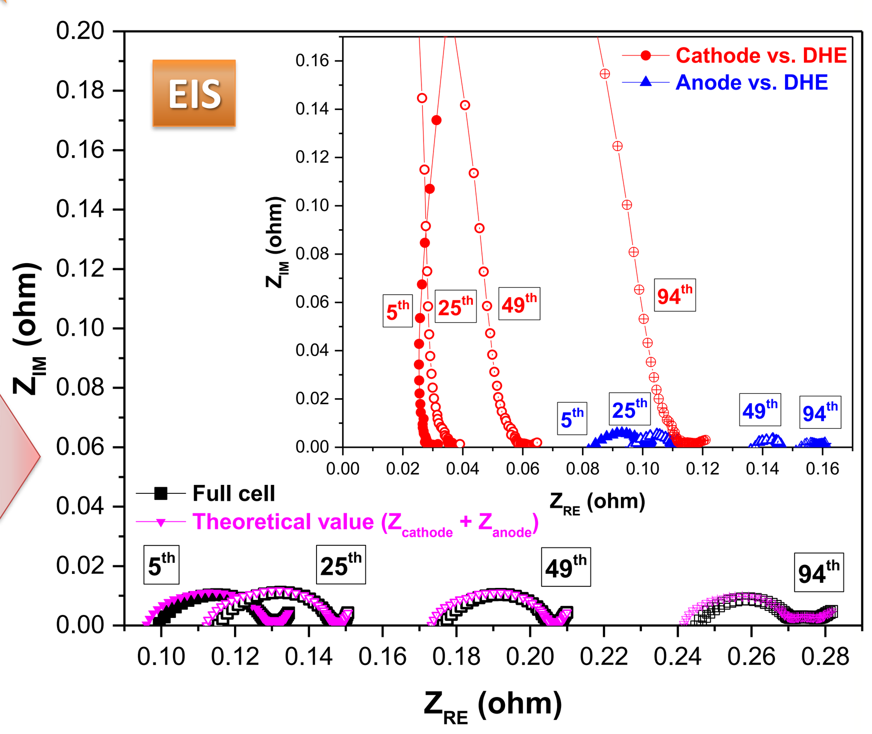


b) *In-situ* monitoring single electrode potential for 100 cycles by extraordinarily stable DHE reference electrode









By DHE approach, the contributions of each electrode to the capacity fading during long-term cycling is disclosed: anode mostly dominates the initial dozens of cycles of capacity fading while cathode participates in the contribution and play a more significant role afterwards. The results agrees well with the EIS measurement of full cell and half cells (cathode or anode vs. DHE) during cycling.

Summary and Perspective:

- A DHE based reference electrode has been developed for VRFB, which demonstrates a superior long-term stability by optimized design with adjustable resistor;
- *In-situ* monitoring single electrode potential has been achieved by the extraordinarily stable DHE throughout 100 cycles of cell charging-discharging;
- By DHE approach, the full cell performance decay (such as capacity, overpotential and impedance distribution) during long-term cycling is dissected into individual electrodes;
- The newly developed DHE approach in scaled commercial VRFB is under validation.

Future Work:

- Single or multi- stressors (including temperature, current density, SOC, DOD and anolyte and catholyte starvation) will be studied to accelerate the VRFB decay;
- ASLT protocol will be established and validated for VRFB with stressor selection;
- VRFB degradation mechanism will be identified by ASLT results.

Acknowledgements

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References:
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2. Chanyong Choi et al. *Electrochim. Acta* 213, 490-495 (2016)
3. Igor Derr et al. *J. Power Sources* 325, 351-359 (2016)
4. Olga Nibel et al. *J. Electrochem. Soc.* 164 (7), A1608-A1615 (2017)

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SNL Energy Storage Technology and Systems – Energy Storage Safety
Funded by Dr. Imre Gyuk
U.S. Department of Energy; Office of Electricity; Energy Storage Systems Program

Materials Science-Based Thermochemical Decomposition Model for Lithium-Ion Battery Thermal Runaway

Randy C. Shurtz, John C. Hewson

Fire Science and Technology, Sandia National Laboratories, Albuquerque, NM

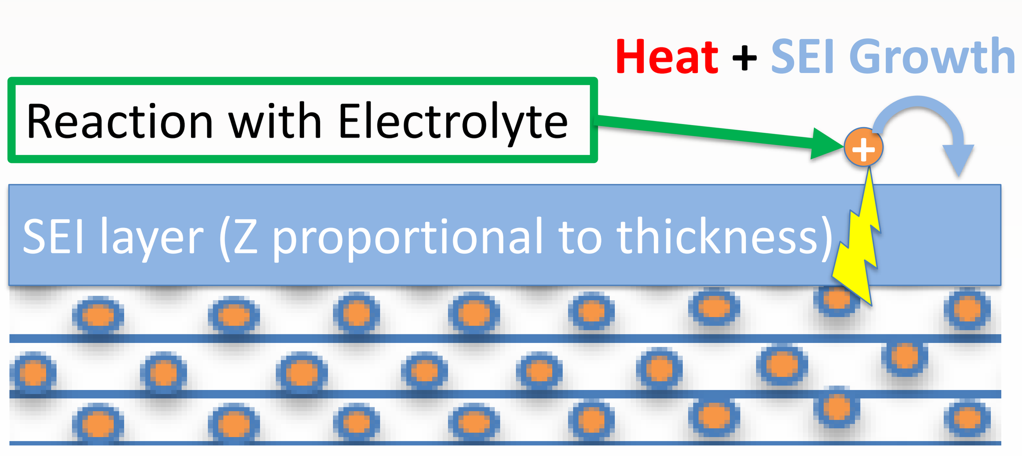
Introduction

- Stationary energy storage systems (ESS) are increasingly deployed to maintain a robust and resilient grid.
- As system size increases, financial and safety issues become important topics.
- Holistic approach: electrochemistry, materials, and whole-cell abuse will fill knowledge gaps.
- Models allow projection of knowledge to different scenarios and larger scales.
- Existing thermal runaway models successful for initial single-cell thermal runaway.
  - Dahn model for graphite anode + $LiCoO_2$ cathode (Hatchard et al. 2001).
- Needed model features to evaluate safety for large Li-Ion systems include:
  - Applicability to batteries with different form factors, chemistries, SOC.
  - Prediction dependent on material properties.
  - High-temperature chemistry to predict propagation.

Anode Decomposition Model Development

Dahn Anode Model (Richard & Dahn 1999, Hatchard et al. 2001)

- SEI formation from electrolyte + intercalated Li limited by electron tunneling.
- Tunneling limitation applied via "z" parameter (proportional to SEI thickness).
- No explicit effect of surface area on z.



= Li in LiC_6 (x_i)
= Li Ion
= Electron Tunneling
= Graphite Layers

Heat Release

$$Q\,[W/g] = -\frac{dx_i}{dt} H_{rxn}$$

Layer Growth | Li_xC_6 Depletion | Li in Li_xC_6 | Temperature Dependence | Electron-Tunneling Limiter

$$\frac{dz}{dt} \propto -\frac{dx_i}{dt} = x_i \quad A_0 \exp\left(-\frac{E_a}{R_g T}\right) \quad \exp\left(-\frac{z}{z_0}\right)$$

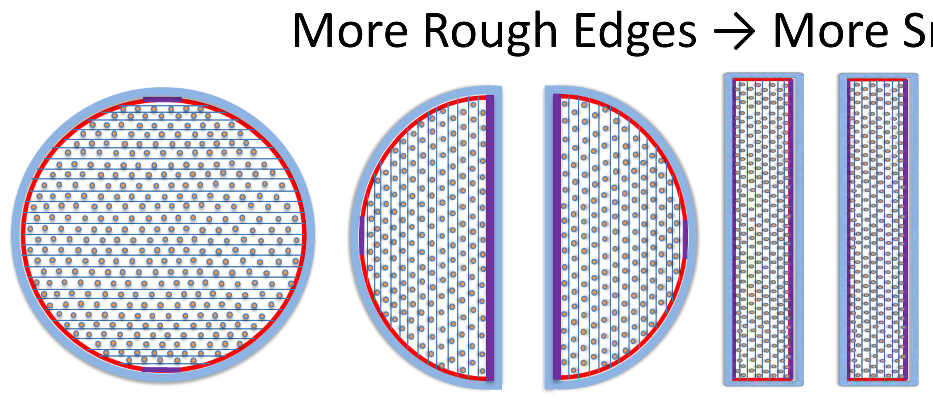
Area-Scaled Model (First Attempt to Upgrade Dahn Model)

- Updated H_{rxn} thermodynamically consistent with complete reaction of all LiC_6

$$2LiC_6 + EC \rightarrow 2C_6 + C_2H_4 + Li_2CO_3$$

- Growth of z scales with reactive surface area (SEI area × defect concentration).
- Defects in SEI more likely when underlying graphite surface is rough (edges).

Round Particles → Flat Particles
Low Surface Area → High Surface Area
More Rough Edges → More Smooth Basal Planes



= Graphite Basal Planes (smooth)
= Graphite Edges (rough)
= SEI Layer

$$\frac{dz}{dt} \propto \frac{A_{rxn,ref}}{A_{rxn}} = \frac{A_{BET,ref} X_{edges,ref}}{A_{BET} X_{edges}} \approx \left(\frac{A_{BET,ref}}{A_{BET}}\right)^{n_1}, n_1 < 1$$

Critical Thickness Model (Area-Scaled Model + Anode Runaway)

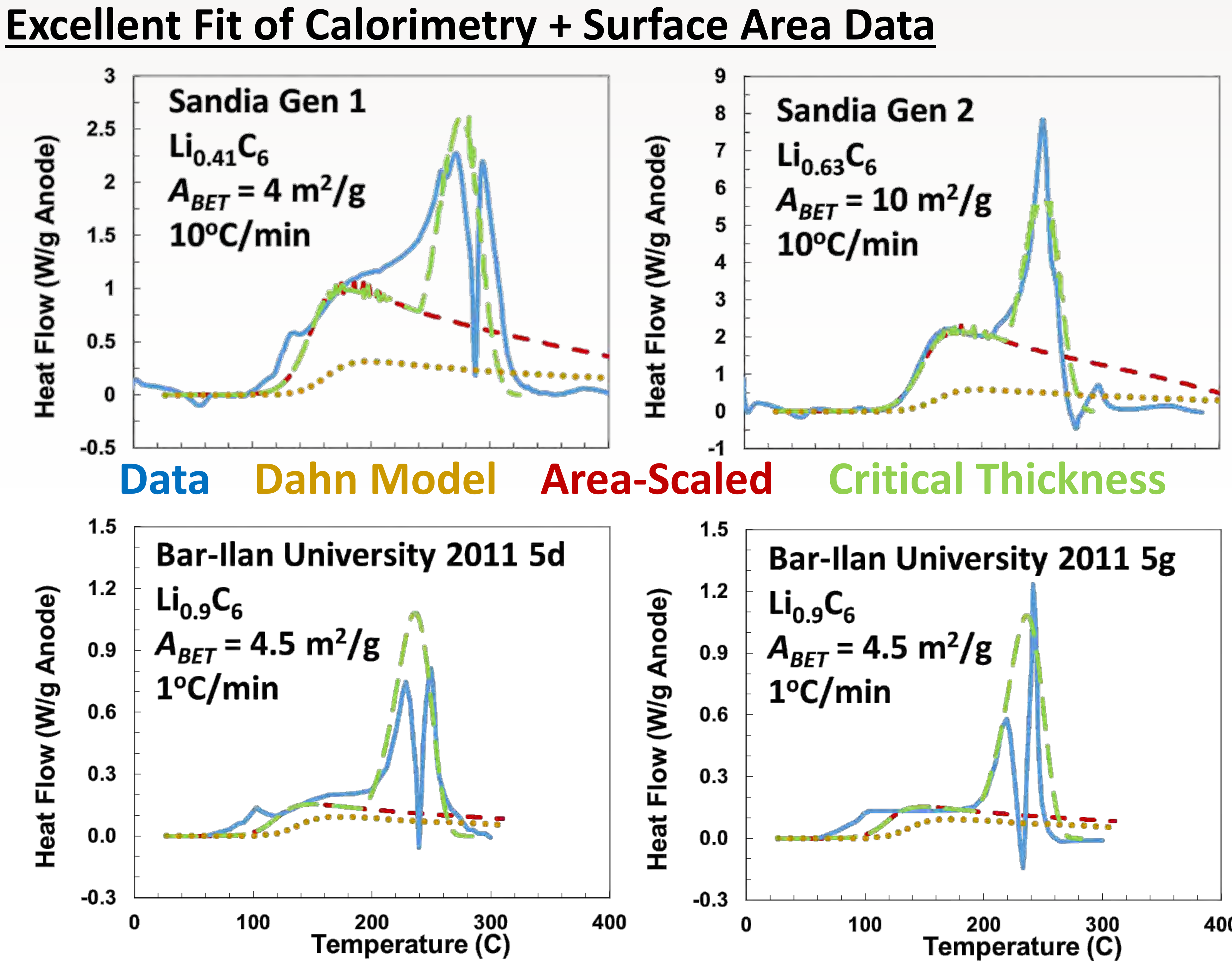
- Effective passivation layer thickness does not increase indefinitely.
- Model limits maximum layer thickness, presumably mechanically limited.

Critical Effective Layer Thickness

$$z = min(z, z_{crit}) \quad \text{where} \quad z_{crit} \propto x_{sei,crit}\left[\frac{A_{BET}}{A_{BET,ref}}\right]^{n_2}$$

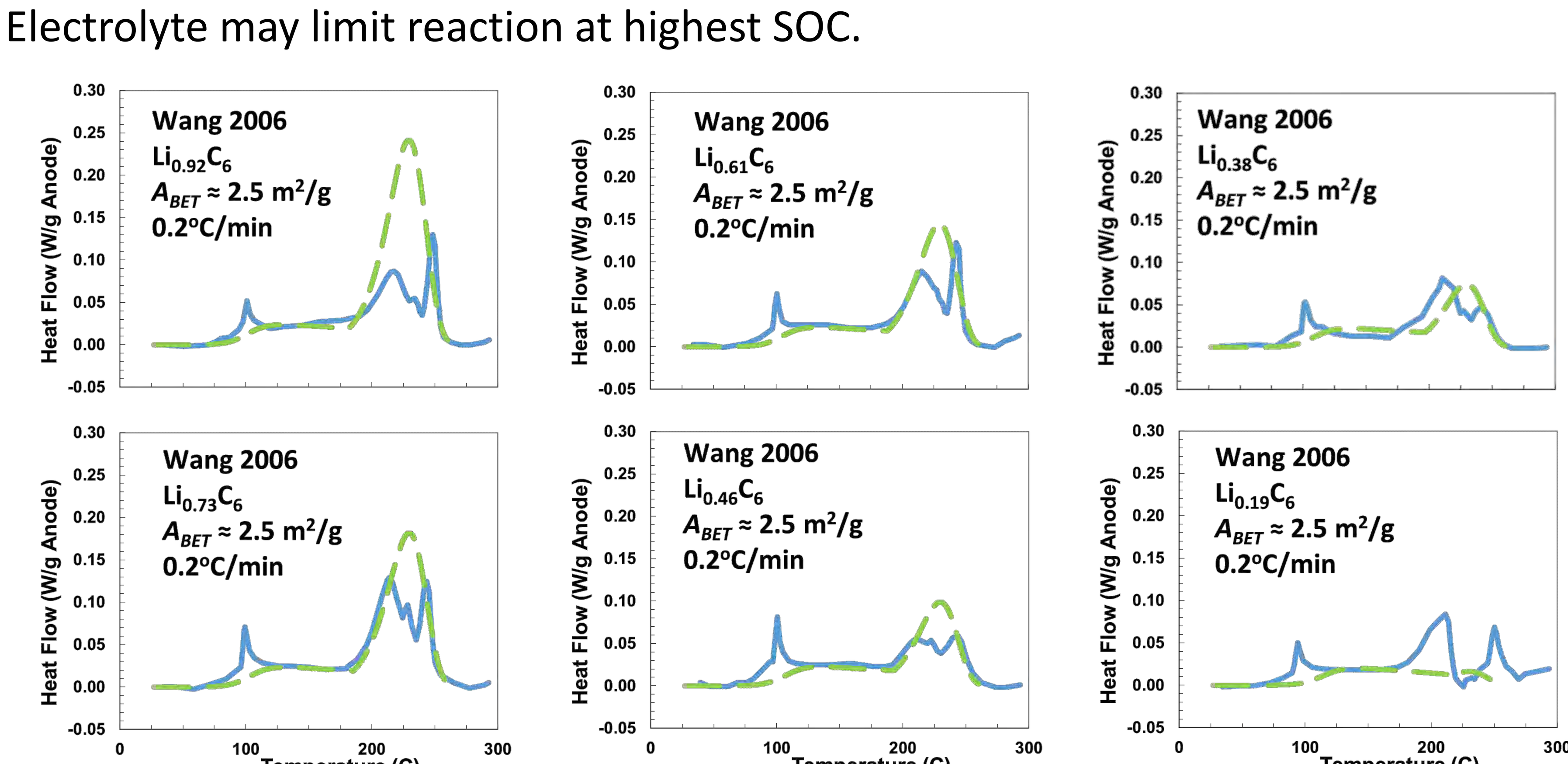
Upgraded Anode Model Performance

Excellent Fit of Calorimetry + Surface Area Data



Final Model Exhibits Proper Trends with State of Charge (SOC)

- A_{BET} estimated (not originally reported).
- Electrolyte may limit reaction at highest SOC.



Summary of Benefits for New Anode Decomposition Model

- More fundamental in terms of thermodynamics and materials science.
- Heat release rates scale properly with material properties, cell build, and SOC.
- High-temperature heat release included; more suitable for propagation studies.

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- Funded by Dr. Imre Gyuk through the U.S. Department of Energy; Office of Electricity
- A special thanks to the following people for providing experimental data, thoughtful discussions, and advice
- Heather Barkholtz • Summer Ferreira • Loraine Torres-Castro • Joshua Lamb • Leigh Anna Steele • Jeff Engerer

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U.S. Department of Energy; Office of Electricity; Energy Storage Systems Program

Modeling Ignition and Cascading Thermal Runaway Behavior in Lithium-Ion Battery Systems

Randy C. Shurtz[1], John C. Hewson[1], and Joshua Lamb[2]

[1]Fire Science and Technology, [2]Power Sources R&D, Sandia National Laboratories, Albuquerque, NM

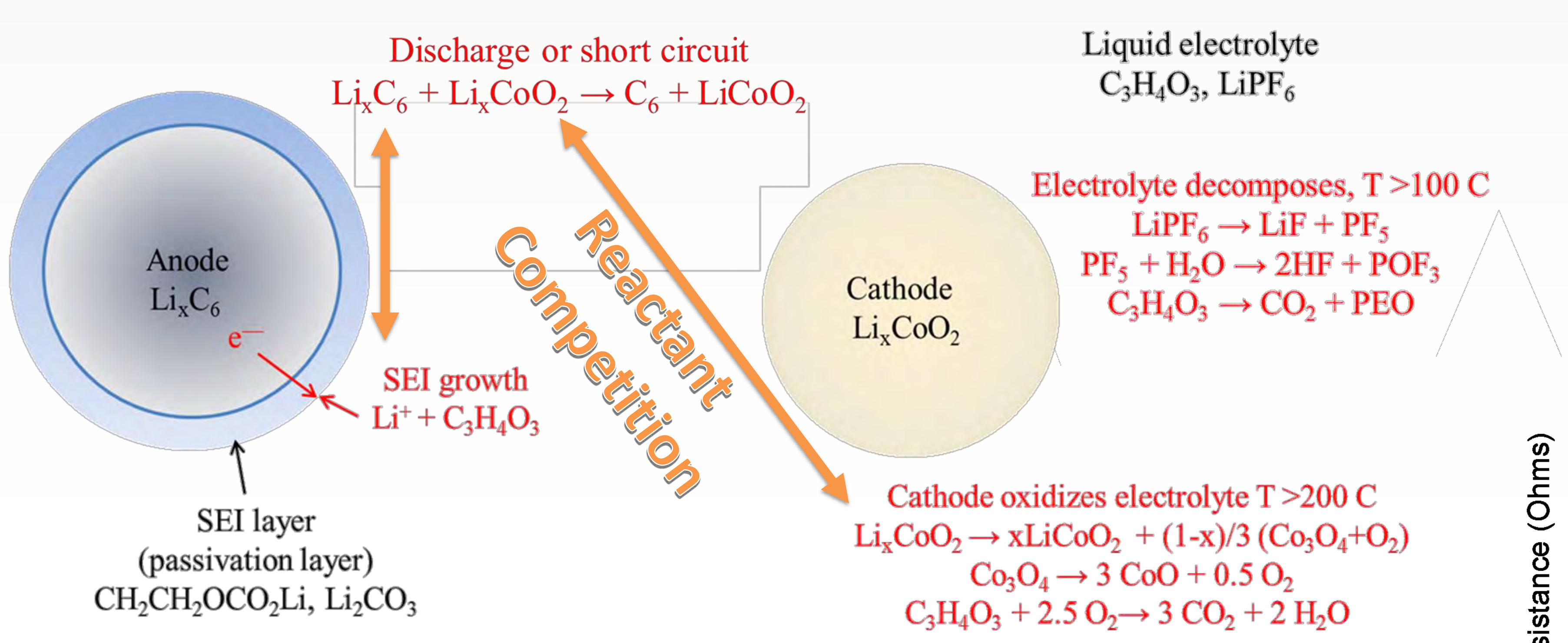
Introduction

- Stationary energy storage systems (ESS) are increasingly deployed to maintain a robust and resilient grid
- As system size increases, financial and safety issues become important topics
- Holistic approach: electrochemistry, materials, and whole-cell abuse will fill knowledge gaps

- Models allow projection of knowledge to different scenarios and larger scales.
- Existing thermal runaway models successful for initial single-cell thermal runaway.
  - Dahn model for graphite anode + $LiCoO_2$ cathode (Hatchard et al. 2001).
- Models with wider applicability under development for cascading failure studies.

Thermal Analogy for Ignition Sources

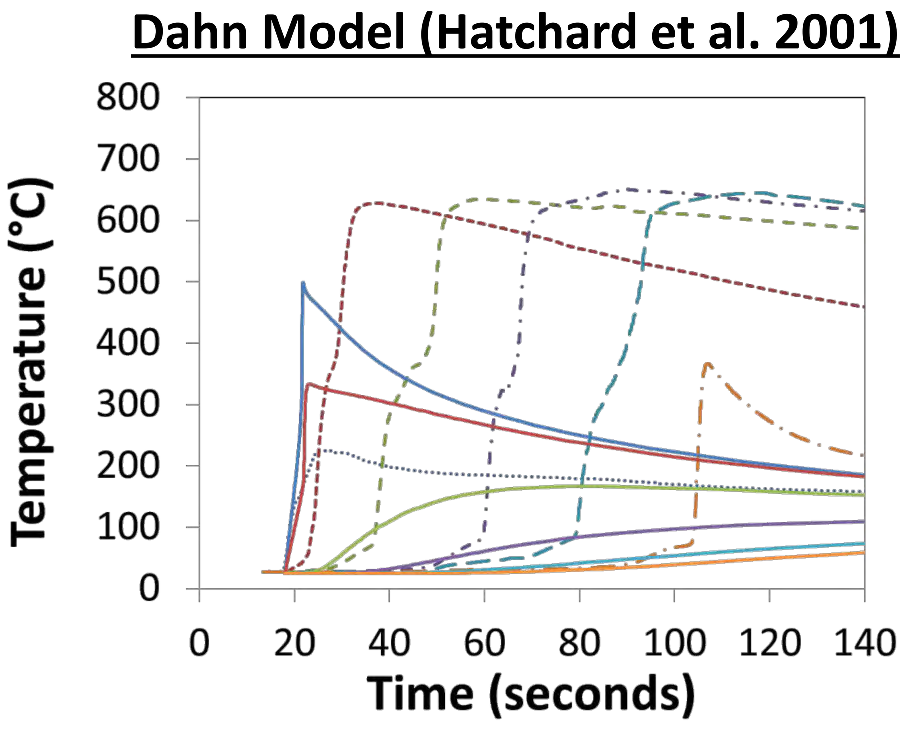
- Energy balance on a cell yields $T_{eff} = T_\infty + P/(h_{net}A)$. where $P = V^2/R$ and $h_{net} = h + h_{rad} = h + \varepsilon\sigma(T_w^2 + T_\infty^2)(T_w + T_\infty)$.
- Short circuit competes with thermal runaway for reactants.
- Oven is representative of short circuit if both T_{eff} and SOC at runaway match.



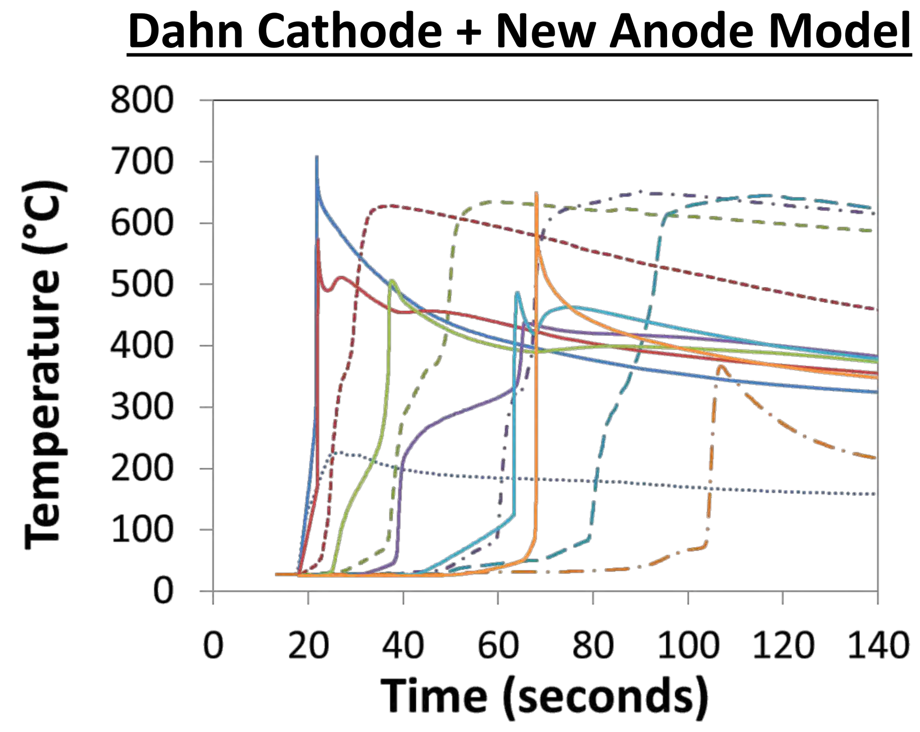
1-D Model of Cascading Failure in Stacked Pouch Cells

- Updated high-temperature reactions improve propagation rate accuracy.
- Propagation rates driven by heat release at highest temperatures.
- Cascading failure model can become more predictive through:
  - Material and thermal property measurements (A_{BET}, initial SEI, $\lambda_\perp$, $\lambda_\parallel$, etc.).
  - More fidelity in high-temperature chemistry models (especially cathodes).
  - Models for venting and separator melting (short circuit resistance).
  - Increased model dimensionality (resolution in 2-D and/or 3-D).

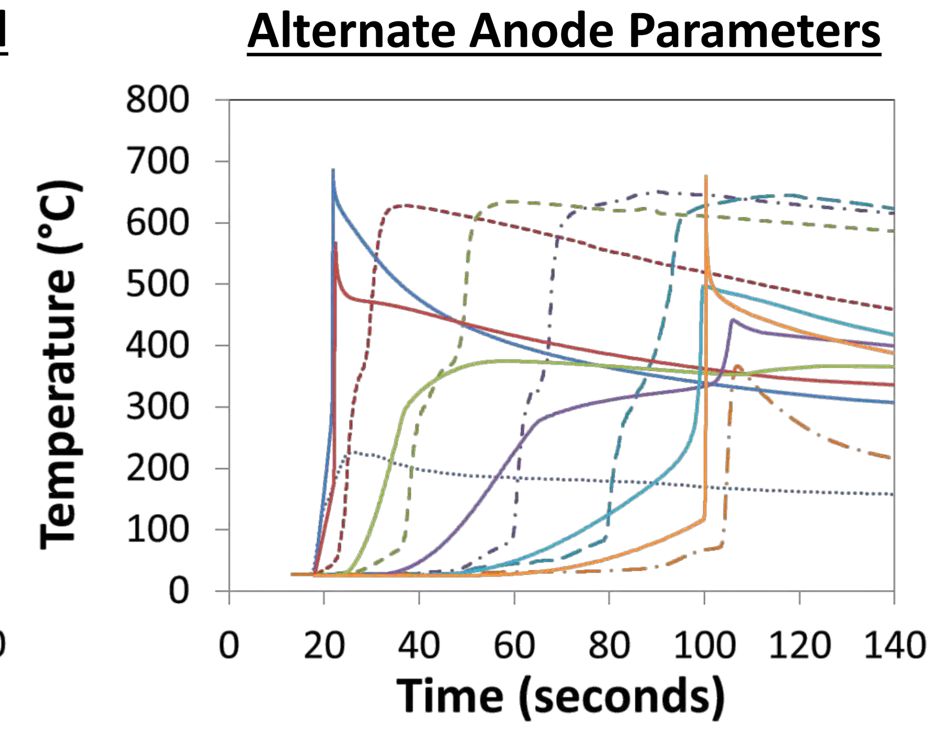
Dahn Model (Hatchard et al. 2001)



Dahn Cathode + New Anode Model



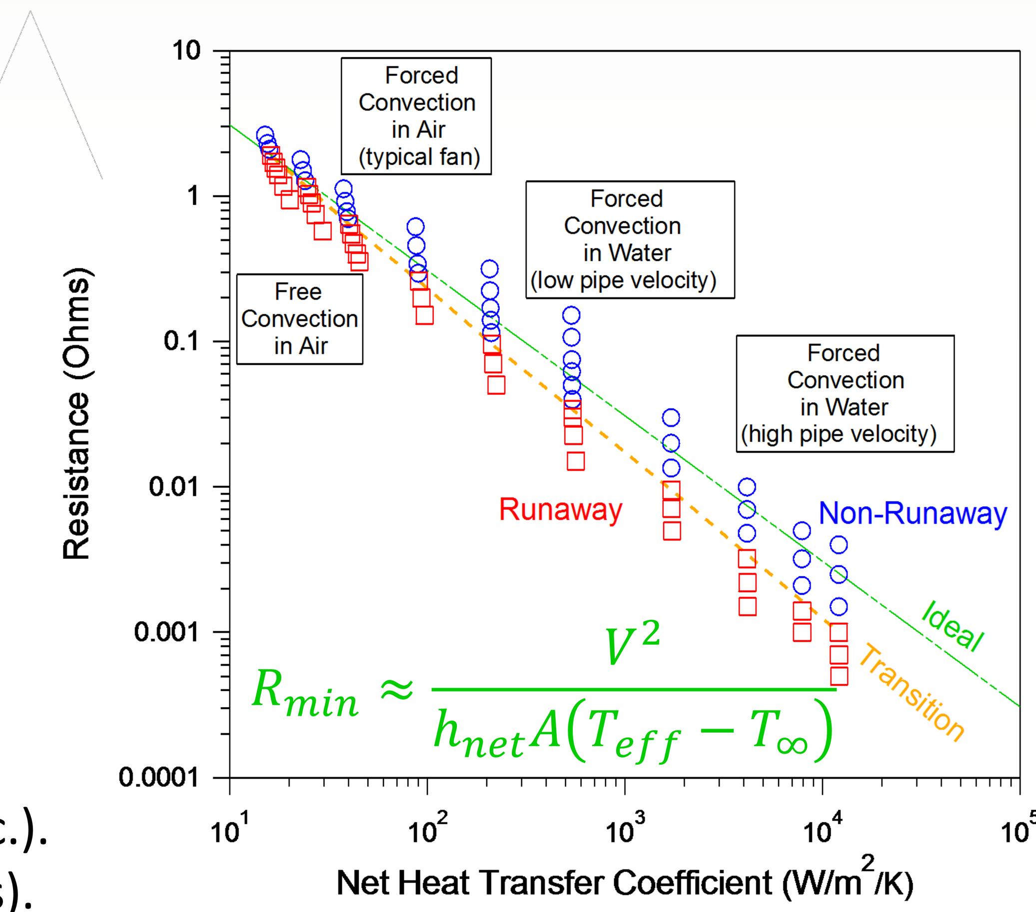
Dahn + New Anode Model, Alternate Anode Parameters



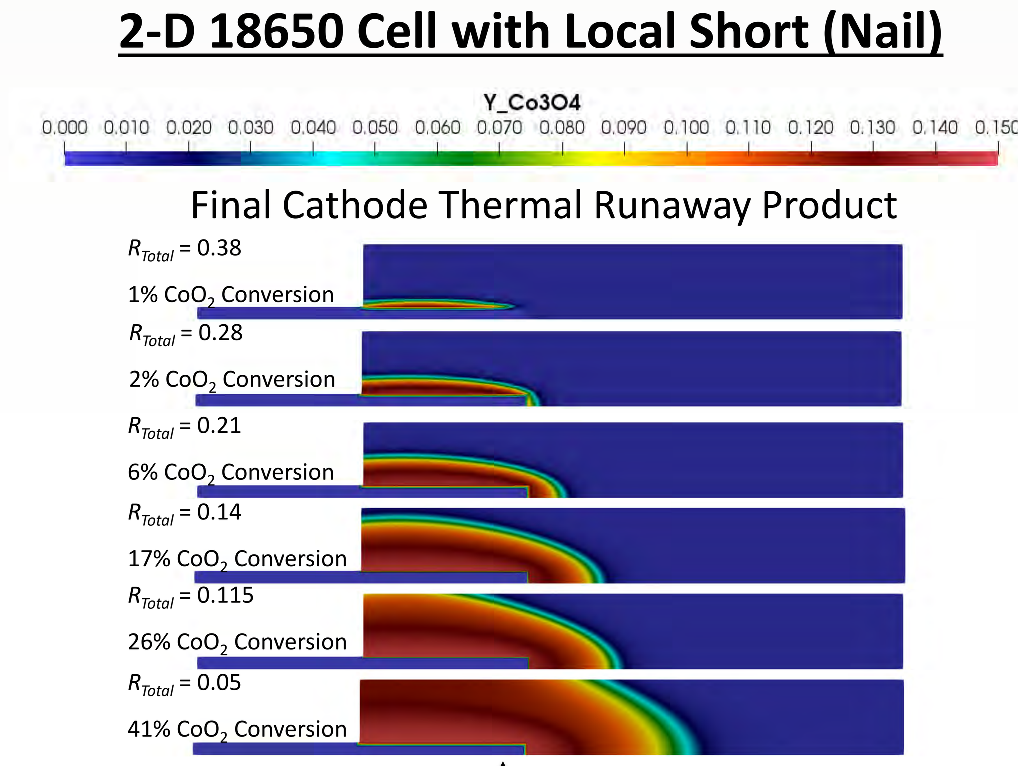
Suppressing Ignition from an 18650 Cell Internal Short Circuit

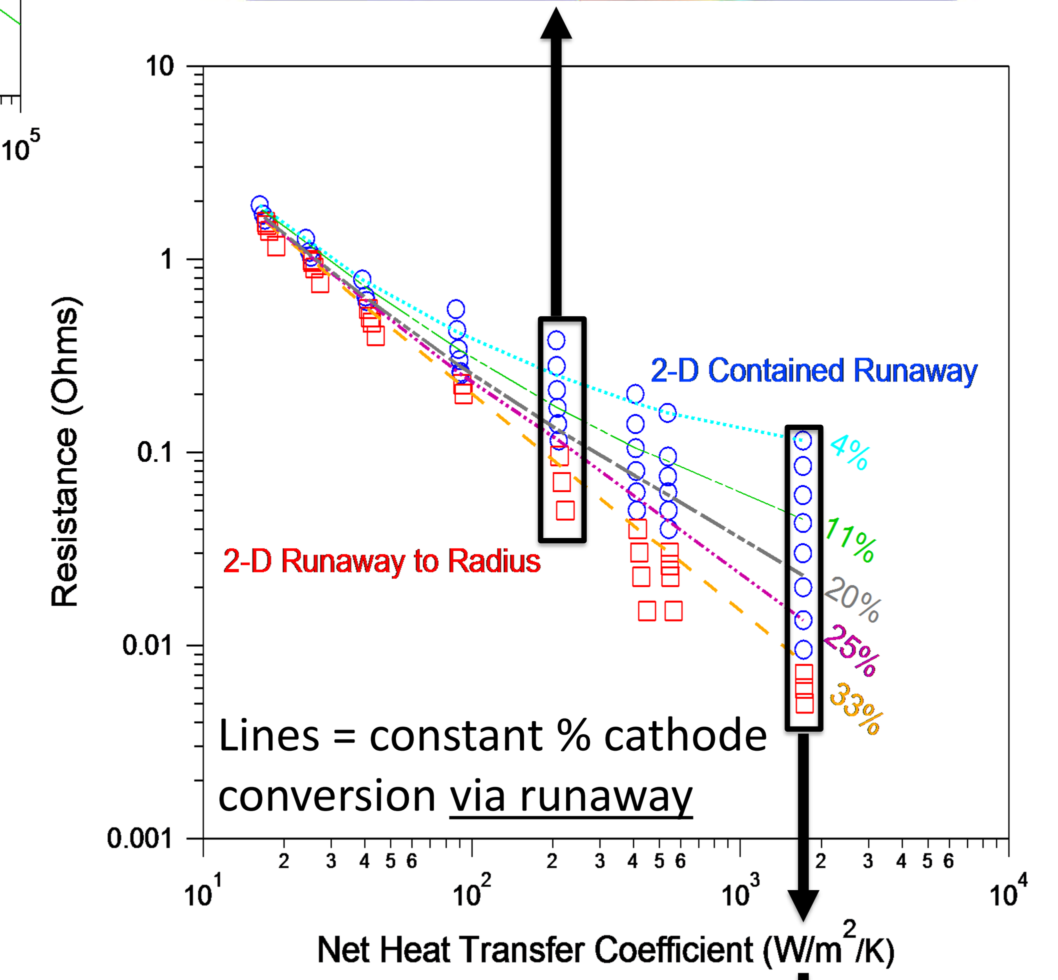
- Given a known internal short circuit resistance and thermal decomposition mechanism, how much cooling is required to suppress thermal runaway?
- Depletion of reactants via short circuits causes deviation from **0-D ideal relationship**.
- Behavior changes for discretized geometry with localized heating and high cooling.
  - Lumped capacitance assumption no longer valid.
  - Cooling and resistance distribution (internal vs. nail) set propagation direction.

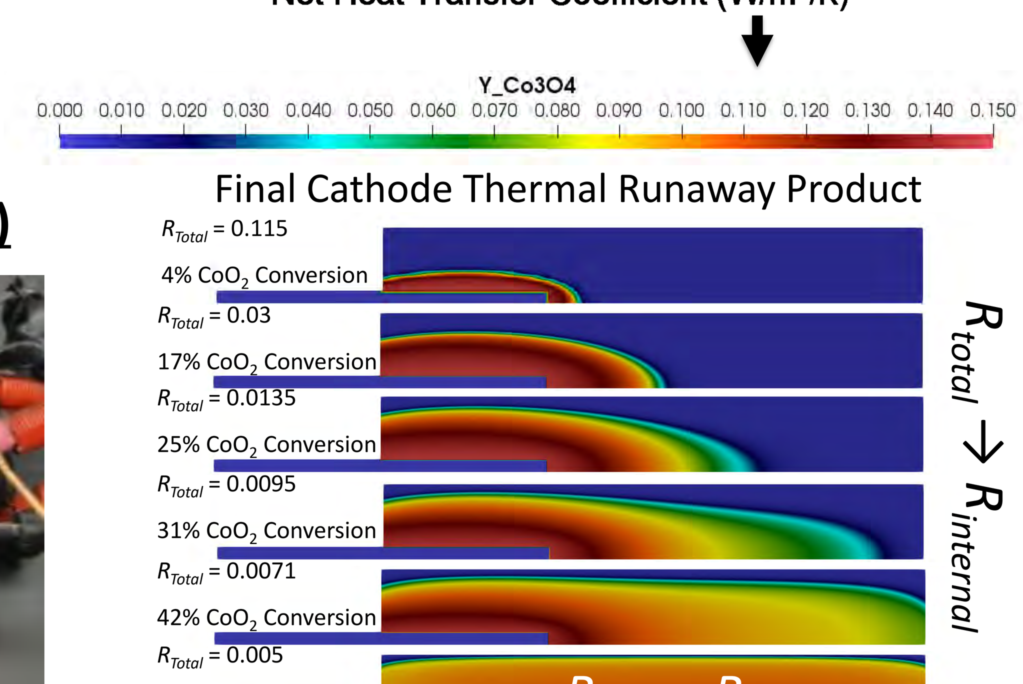
0-D 18650 Cell with Uniform Heating



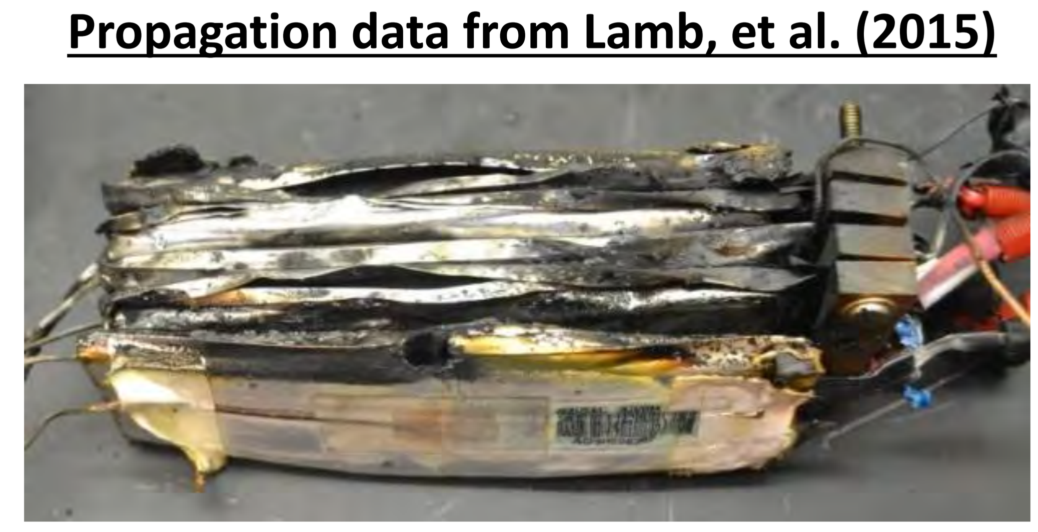
2-D 18650 Cell with Local Short (Nail)







Propagation data from Lamb, et al. (2015)



In Summary

- Models enable detailed analysis of ignition and propagation trends.
- Thermal analogy for ignition is a useful tool to compare different scenarios.
- Simultaneous short circuit and runaway implies competition for reactants.
- Predictive power of propagation models improves as high-temperature chemistry models are implemented.

U.S. DEPARTMENT OF ENERGY NNSA National Nuclear Security Administration

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Acknowledgements:
- Funded by Dr. Imre Gyuk through the U.S. Department of Energy; Office of Electricity
- A special thanks to the following people for providing experimental data, thoughtful discussions, and advice
- Heather Barkholtz • Summer Ferreira • Loraine Torres-Castro • Leigh Anna Steele

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Oregon and Washington Storage Regulatory Policy

Rebecca O'Neil, Patrick Balducci, Kendall Mongird

Pacific Northwest NATIONAL LABORATORY

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Problem

State utility regulatory commissions are charged with balancing private utility investment opportunities, reliable system operations, and ratepayer interests. In considering the value of new technologies, state commissions often rely on independent third parties such as the US Department of Energy for credible information and analysis. In FY17, both the Washington Utilities and Transportation Commission and the Oregon Public Utility Commission embarked on energy storage-specific dockets and requested support from Pacific Northwest National Laboratory to execute these dockets.

Objectives

1. Create more informed regulatory outcomes for energy storage technologies through infusing technical expertise and analysis into seminal regulatory commission actions [impact]
2. Connect state regulatory commissions with the breadth of the technical research program at US DOE Office of Electricity at an accessible level [durability]

Overall Aim

This project supports the Office of Electricity mission by facilitating direct technical partnerships between the Energy Storage Program and key stakeholders, in pursuit of a resilient, reliable, and flexible system. The project implements seminal state activities as part of the Equitable Regulatory Environment thrust as described in the Program strategy *Grid Energy Storage*, December 2013.

Iterative Improvement to Inform Program Delivery

In service to the US DOE Energy Storage Program, PNNL engages with states across the country to share best practices, consider the range of regulatory approaches as best adapted to the state perspective, and provide analytical insight. The Washington and Oregon case studies provide a unique opportunity for PNNL to tailor its research program to best suit the regulatory commissions most immediate needs, maximizing impact and broadening opportunities for the private sector.

Advancing the State of the Art

When Storage Program research is applied to regulatory proceedings, unique insights can be achieved. Then the research program to continue to move into pioneering territory as industry, regulatory, and utility approaches deepen and become more established.

Example Collaboration from Storage Program to the Regulatory Environment

PNNL adapted the US DOE Energy Storage Handbook use cases for Oregon utilities, and through feedback and stakeholder workshops, advised Commission Staff on a foundational suite of use cases for utility system evaluations for storage applications.

Energy Storage Use Cases

Current Use Cases Identified by Staff

Category	Service	Value
Bulk Energy	Capacity or Resource Adequacy	The ESS is dispatched during peak demand events to supply energy and shave peak energy demand. The ESS reduces the need for new peaking power plants.
	Energy arbitrage	Trading in the wholesale energy markets by buying energy during low-price periods and selling it during high-price periods.
Ancillary Services	Regulation	An ESS operator responds to an area control error in order to provide a corrective response to all or a segment portion of a control area.
	Load Following	Regulation of the power output of an ESS within a prescribed area in response to changes in system frequency, tie line loading, or the relation of these to each other, so as to maintain the scheduled system frequency and/or established interchange with other areas within predetermined limits.
	Spin/Non-spin Reserve	Spinning reserve represents capacity that is online and capable of synchronizing to the grid within 10 minutes. Non-spin reserve is offline generation capable of being brought onto the grid and synchronized to it within 30 minutes.
	Voltage Support	Voltage support consists of providing reactive power onto the grid in order to maintain a desired voltage level.
	Black Start Service	Black start service is the ability of a generating unit to start without an outside electrical supply. Black start service is necessary to help ensure the reliable restoration of the grid following a blackout.
Transmission Services	Transmission Congestion Relief	Use of an ESS to store energy when the transmission system is uncongested and provide relief during hours of high congestion.
	Transmission Upgrade Deferral	Use of an ESS to reduce loading on a specific portion of the transmission system, thus delaying the need to upgrade the transmission system to accommodate load growth or regulate voltage or avoiding the purchase of additional transmission rights from third-party transmission providers.
Distribution Services	Distribution Upgrade Deferral	Use of an ESS to reduce loading on a specific portion of the distribution system, thus delaying the need to upgrade the distribution system to accommodate load growth or regulate voltage.
	Volt-VAR Control	In electric power transmission and distribution, volt-ampere reactive (VAR) is a unit used to measure reactive power in an AC electric power system. VAR control manages the reactive power, usually attempting to get a power factor near unity (1).
	Outage Mitigation	Outage mitigation refers to the use of an ESS to reduce or eliminate the costs associated with power outages to utilities.
	Distribution Congestion Relief	Use of an ESS to store energy when the distribution system is uncongested and provide relief during hours of high congestion.
Customer Energy Management Services	Power Reliability	Power reliability refers to the use of an ESS to reduce or eliminate power outages to utility customers.
	Time-of-Use Charge Reduction	Reducing customer charges for electric energy when the price is specific to the time (season, day of week, time-of-day) when the energy is purchased.
	Demand Charge Reduction	Use of an ESS to reduce the maximum power draw by electric load in order to avoid peak demand charges.

Source: Modified from Akhil et al. 2015.

MEMORANDUM OF UNDERSTANDING AREAS OF COOPERATION with the OREGON PUC

- *Use cases and services derivation; calculation methodologies; review of system benefit analysis***.** Staff anticipates the need to review and validate the services and use cases presented by the utilities and stakeholders both in the initial stakeholder discussions and workshops and during Staff and Commission review of utility proposals. Valuation of each use case and the total benefits of a storage system will be based on complex models and utility system-specific deferral or services values. PNNL intends to review use case architectures based on services identified in other site-specific analyses in the Northwest; to assess the completeness of use cases proposed for evaluation; and to advise on methodologies for defining the value of a use case; to evaluate modeling approaches to ensure they effectively capture energy storage characteristics and co-optimize between services.
- *Technology capability validation.* PNNL has developed models that accurately characterize battery performance as differentiated by use case, state of charge range and ambient temperature. These models were developed from the extensive testing of grid-connected lithium-ion and vanadium redox flow batteries. PNNL may also be able to provide data and validate assumptions related to battery costs. PNNL intends to advise the Commission and the utilities as requested regarding storage performance capabilities and operational characteristics, which in turn supports technology selection and accurate models.
- *Staff support, subject matter expert for sound policy development.* Energy storage systems are an emerging technology with many applications, designs, and quickly advancing cost and performance outlook. Staff will collaborate with external subject-matter experts to validate utility assumptions. Having a subject-matter expert such as PNNL to provide support to Staff will help speed the review process and help meet the Commission's timelines and goals. PNNL will respond to questions and support Staff and the Commission as requested, in particular in support of Staff's effective execution of workshops.

MEMORANDUM OF UNDERSTANDING AREAS OF COOPERATION with the WASHINGTON UTC

- *Record analysis and development.* PNNL will support UTC review of the public comment record, resolve questions (e.g., performance characteristics and learning rates) which can be supplied to the docket and public record, and support record development and citation for the policy statement.
- *Modeling approach.* PNNL will educate UTC staff and commissioners on best practices on utility siting, sizing, technology selection, identifying use cases and associated values with those use cases, and how modeling can support economic feasibility. PNNL will provide the UTC with relevant direct deployment and valuation experience from around the country, in particular Washington Clean Energy Fund efforts. PNNL will work with the UTC to consider how these approaches could best fit the regulatory framework.
- *Drafting and consultation.* PNNL will support UTC drafting of policy statements on request. It should be noted that PNNL does not have an independent interest in a regulatory outcome that favors a technology or an approach.
- *Publication.* PNNL will support the final publication of a policy statement, reporting to DOE on the specific outcome, on its relevance and utility for other states and for the objectives of the Energy Storage Program.

Service Date: March 6, 2017

BEFORE THE WASHINGTON STATE UTILITIES AND TRANSPORTATION COMMISSION

In the Matter of the Washington Utilities and Transportation Commission's Investigation into Energy Storage Technologies.	DOCKETS UE-151069 AND U-161024 DRAFT REPORT AND POLICY STATEMENT ON TREATMENT OF ENERGY STORAGE TECHNOLOGIES IN INTEGRATED RESOURCE PLANNING AND RESOURCE ACQUISITION

DRAFT POLICY STATEMENT RECOMMENDATIONS

- Establishes energy storage in policy. "It is the policy of this Commission that energy storage is a key enabling technology for utilities to comply with the state's energy policies, and that Washington's investor-owned utilities should be diligently working to identify and pursue cost-effective opportunities to incorporate energy storage into their systems."
- Utilities must evaluate storage if they want to make a major investment.
- Directs utilities to transition to sub-hourly models for future IRPs, and adopts a "net cost" approach in the interim.
- Directs utilities to consider a range of storage technologies, and to use learning curves, or reducing cost curves, when estimating storage in the future.
- Encourages transparency of data and for utilities to procure storage systems competitively.
- Acknowledges that storage solutions may not be the least cost solution, but may still be selected given the non-quantifiable benefits.
- Opens the door to new tariff designs that support behind the meter storage.

Oregon Public Utility Commission

Oregon Public Utility Commission

Docket UM 1751

MOU Signed: December 15, 2016

Docket Status: Staff Recommendations on Draft System Evaluations, Draft Project Proposals Due January 1, 2018

Key Results: Informed multiple Staff memos, earning quick ALJ and Commission approvals; system evaluations and project proposals will drive storage modeling advances; Staff empowered to engage in secondary storage actions, e.g. planning and procurement guidelines

"Also I'd like to note the invaluable assistance and support staff received from Staff from the Pacific Northwest National Lab, Rebecca O'Neil and Patrick Balducci. Without their knowledge and professional insight and recognized expertise Staff would not have been able to make the progress we have in the short time allowed." OPUC Staff Jason Klotz, Commission Meeting March 21, 2017

Washington Utilities and Transportation Commission

Dockets UE-151069 and U-161024

MOU Signed: March 4, 2017

Docket Status: Draft Policy Statement Issued March 6, 2017

Key Results: Timely and credible delivery of storage technology information; advisory role in weighing the merits of multiple approaches in a draft policy statement; continuous updates and engagement to facilitate final policy statement development.

WASHINGTON UTC UTILITIES AND TRANSPORTATION COMMISSION

"Members of the Commission and Staff attended an informational workshop on the topic of energy storage at the Pacific Northwest National Laboratory (PNNL) on July 22-23, 2015. The workshop was designed for utility regulators and staff from the Pacific Northwest to understand recent advances in energy storage and discuss the technology's potential impact on grid operations. Commissioners and staff from the states of Idaho, Montana, Oregon and Washington attended the workshop. At the Commission's request, PNNL staff subsequently presented a summary of the information from this informational workshop at a public workshop of the Commission." P. 1-2 of the Draft Policy Statement.

U.S. DEPARTMENT OF ENERGY

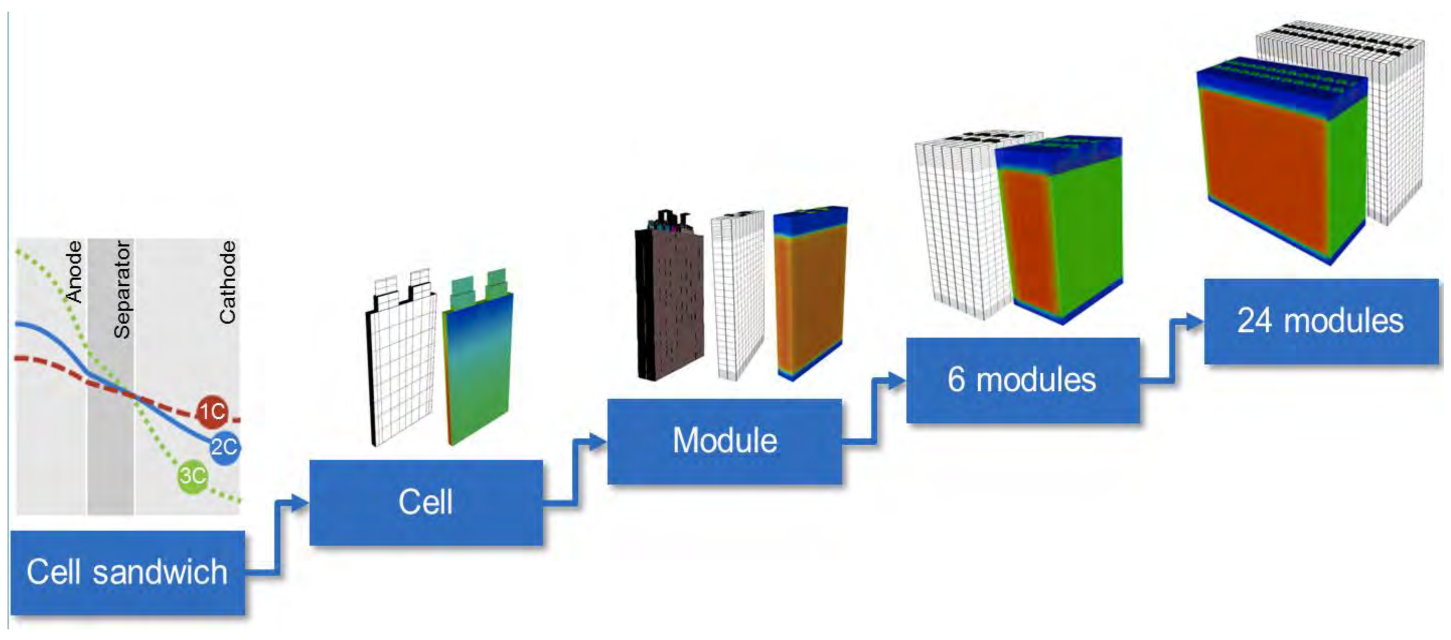
PNNL-SA-129725

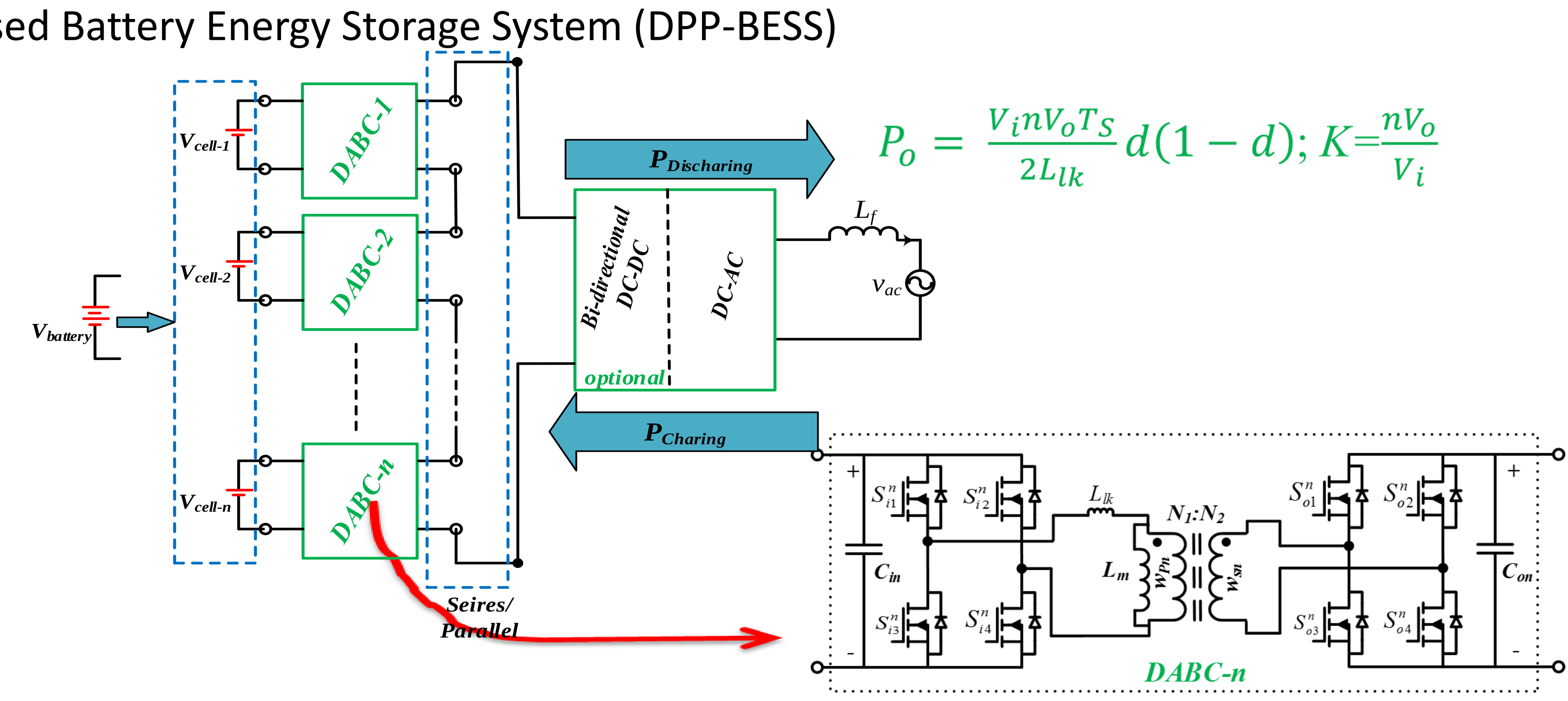
Sandia National Laboratories

NM STATE UNIVERSITY

OFFICE OF ELECTRICITY DELIVERY & ENERGY RELIABILITY

Distributed Power Processing structure based Battery Energy Storage System (DPP-BESS)





Distributed power processing for Li-ion batteries

Nataraj Pragallapatti Satish Ranade Javier Alvidrez Ankith Nadella Jose Tabarez
Klipsch School of Electrical Computer Engineering New Mexico State University,
Las Cruces, NM

Stan Atcitty M A Moonem
Sandia National Laboratories
Albuquerque, NM

Purpose and Impact

Investigate potential benefits of processing energy at the unit level (battery, cell) with subsequent series parallel connections

- improved efficiency of the overall stack?
- improved safety and reliability through battery level analytics?

Description

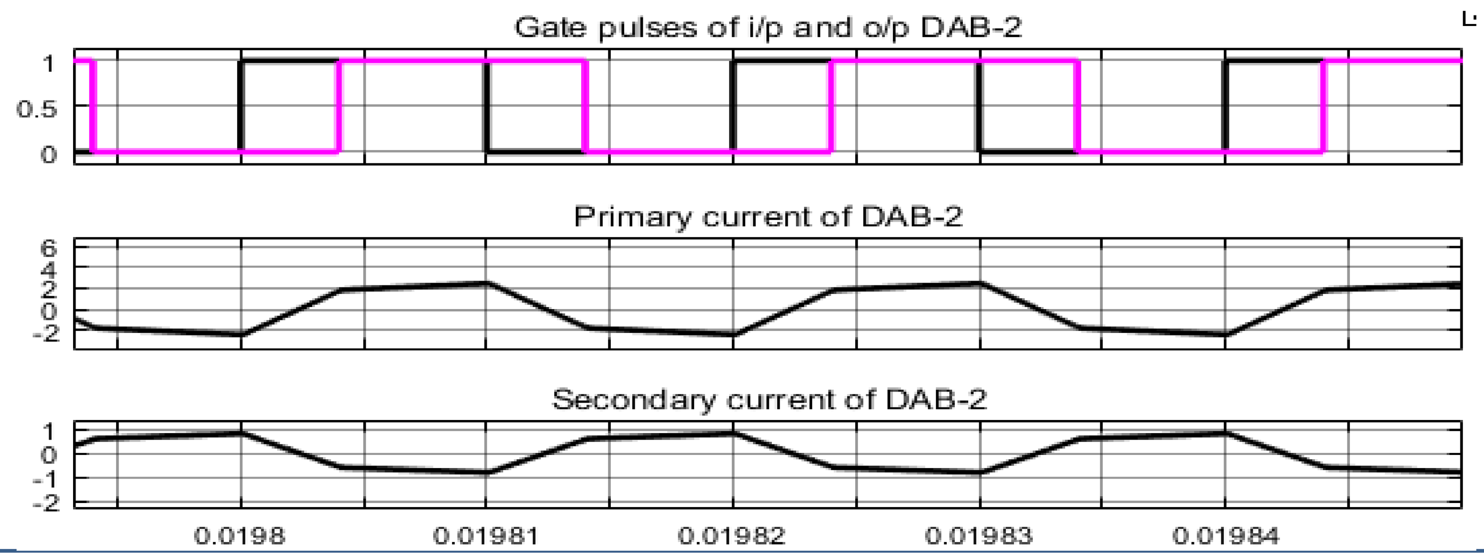
Design and development of Distributed Power Conversion circuits based Battery Energy Storage System (DPCC-BESS) for the stationary, grid-tied applications.

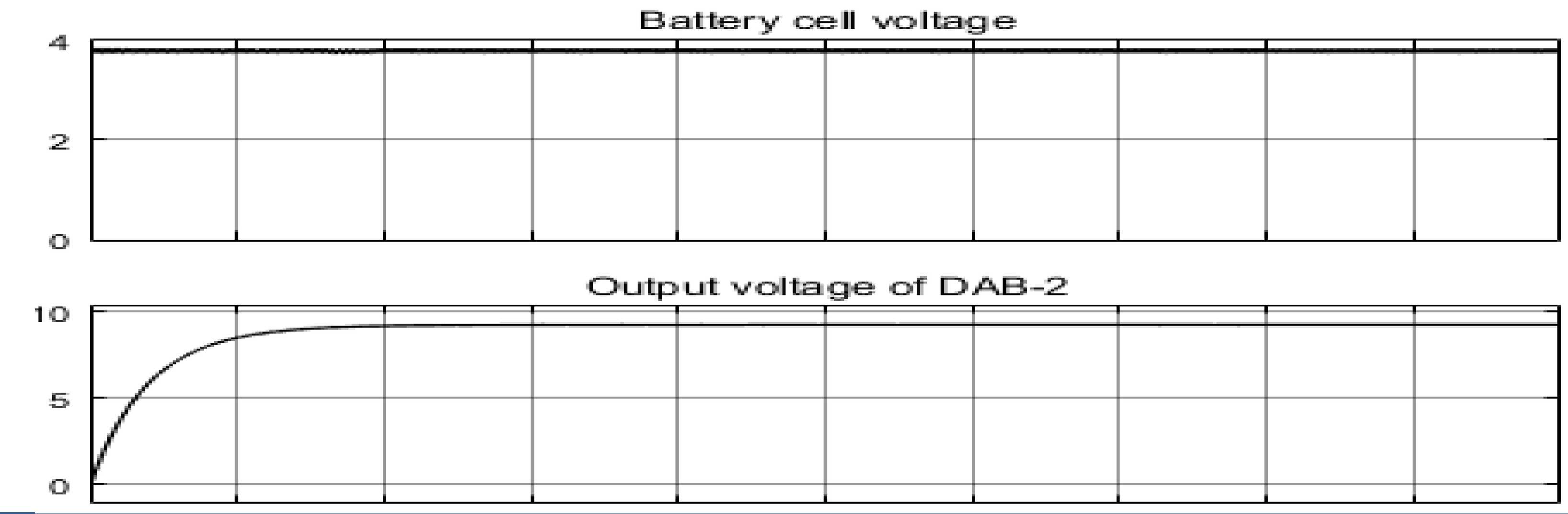
The deliverables of the Project are:

- Optimized Power processing battery/cell level.
- System efficiency improvement by the use of advanced power electronics devices.
- Optimized PCB close to the size of battery/cell.
- High-frequency Transformer design and Bi-directional power control of DAB at battery/cell level.

Preliminary simulation results of two (Li-ion) cells with DPP (DAB). Open-loop at 80% Load

Parameters of DAB: Optimum Parameter values: L_{lk} = 31µH; Phase shift (d)= 0.24; Voltage conversion ratio (K)=0.95; Ratings of DAB: P=7.5W, V_i=3.3V, V_o=10V.





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This work is supported by the Department of Energy, Energy Storage Program management by Dr. Imre Guyk.

U.S. DEPARTMENT OF ENERGY NNSA National Nuclear Security Administration

Stephen Gómez[1], Morgan Henrie[2], Dan Borneo[3] and Babu Chalamala[3]
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SAND2017-10739 C

PEER REVIEW 2017
EVOLUTION & REVOLUTION
San Diego, California | October 9-10, 2017

Workforce Development for the Future Grid

- The US Dept. of Labor (DOL) projects that there will be an increase of ~14,000 jobs for electrical power-line installers and repairers from 2014 to 2024. A large part of the growth will be due to upgrading the interstate power grid (Fig. 1).
- Global battery-making capacity is set to more than double by 2021. It has been reported that a large battery production plant could create 7,000 jobs during construction and require 300 full-time jobs after start up.
- Energy storage is not considered an occupational field by the DOL
- Storage Battery Tester description hasn't been updated since 2001.
- Figure 2 is an actual job posting sent to SG in Aug 2017.
- There has been ZERO response for a $25-30/hr position.
- This journeyman does not currently exist.

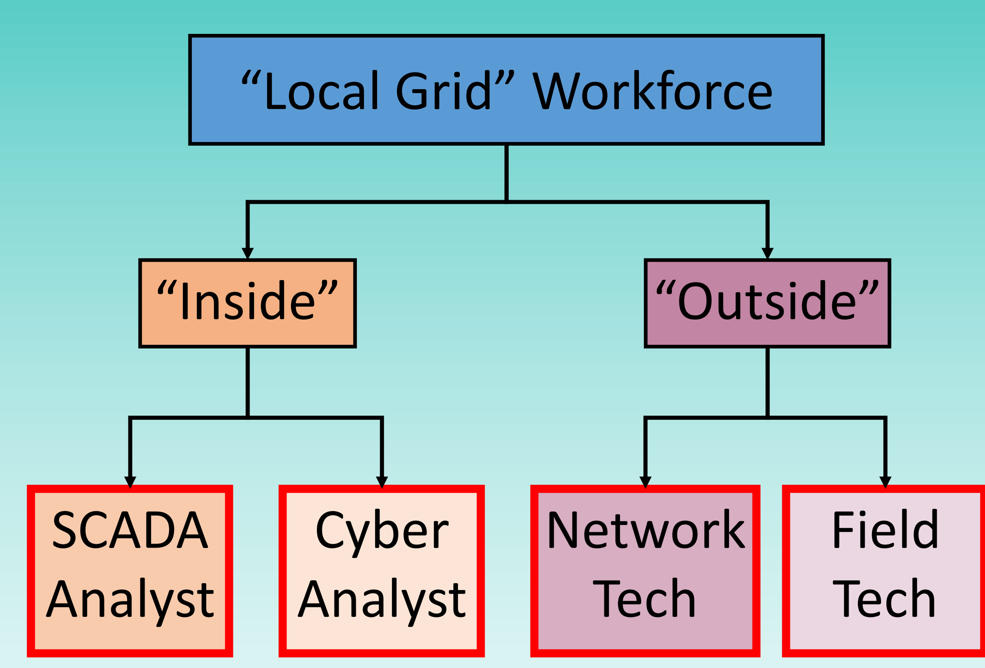

Figure 1. Schematic of generalized occupation categories for smartgrid technicians.

Sent: Tuesday, August 22, 2017 12:59 PM
To: Stephen Gomez
Subject: Job Posting for Trades Building

Hi Steve,
I am with [redacted] and we are seeking a qualified journeyman electrician.
I have been tasked with this recruiting effort and it seems we are having a bit of difficulty finding a qualified person for this role.
I am not sure what the problem is specifically but I hope we can get some response from a job post on the trades building job board,
Below is the fundamental job requirements for the Journeyman Electrician person that we are seeking.

A rapidly expanding solar energy company is seeking a professional Journeyman Electrician with at least 2+ years of solar experience with:

- **PV to grid interconnection**
- **Battery storage and off-grid systems experience**
- **Ability to lead a crew in field and proven supervisory skills**
- **Project management skills with great organizational ability**
- **Customer service, good interpersonal skills**
- **Controls experience a plus**
- **NM Journeyman card in good standing & valid NM driver's license**

If you consider yourself a top notch and conscientious employee, we are interested. Please submit a resume and 2 professional references or call 505-[redacted] for more details on applying.
Job Type: Full-time
Salary: $25.00 to $30.00 /hour with PTO

Thanks Steve. Call me with any questions at 505-[redacted].

Figure 2. Job posting sent to SG in Aug 2017.

- Local grid and energy storage industry is growing rapidly, but the line workers and technicians of today do not possess the skill sets for these new jobs and this aging workforce is unlikely to undertake the training required to acquire these new skills.
- SFCC is a HSI that is 80% energy sovereign and has developed a new 2-yr *Certificate in Electrical, Smart Grid and Micro Grid Technologies* (22 hrs) embedded in the Engineering Technologies AAS degree.
- Courses have been developed in generation/transmission/distribution and management (ELEC 151, ELEC 201), but not in energy storage.
- Curriculum for an energy storage class developed during a summer faculty sabbatical at SNL for a 16-week class directed towards the 2-yr technical student is shown in Fig. 3.

		1st 4 weeks			2nd 4 weeks			3rd 4 weeks			4th 4 weeks
Week 1	1	Admin/Grading/Safety/Energy Storage Intro	Week 5	1	Pumped storage	Week 9	1	Lead Acid – Current Technology	Week 13	1	Fly Wheels/Compressed air
	2	Energy/Electricity/US Generation Mix/Trends		2	Intro to batteries (discovery, chemistry/half-cell, hurdles)		2	Lead Acid – Research/Future Technology		2	Field Trip/Guest lecture (dates adjustable)
Week 2	1	Generation/Transmission/Load Balancing/Distribution Review	Week 6	1	Battery types (wet cell, dry cell, flow cell, fuel cell, "microbial"?)	Week 10	1	Li-ion – various chemistries/optimal uses	Week 14	1	Field Trip/Guest lecture (dates adjustable)
	2	North American Grid/Reliability/Security/Failures/"Ideal" grid		2	Battery Commissioning		2	Li-ion – advantages and disadvantages		2	Student Presentations (start large class) Lecture (small class)
Week 3	1	Conservation/Efficiency/Line loss/HVDC transmission	Week 7	1	Storage-Load Balancing/Peak smoothing/Arbitrage	Week 11	1	Flow Batteries – types/optimal uses	Week 15	1	Student Presentations (finish large class) Start (small class)
	2	Energy Markets/Arbitrage/ROI for energy storage systems		2	Codes - overview		2	Flow Batteries – advantages and disadvantages		2	Exam Review
Week 4	1	Energy Storage (overview of types of storage, details later)	Week 8	1	Midterm Exam	Week 12	1	Others – Molten NaS, Zebra, $ZnMnO_2$, Salt Water	Week 16	1	Final Exam
	2	Microgrid/Smartgrid (overview how storage makes it possible)		2	Review Midterm – Choose project (Adopt A Technology)		2	Fuel Cells			

Figure 3a. 16-week curriculum for Energy storage at the 2-yr technician level.

	Week 2 Day 1 (Lecture 3)	
1st 15' module	Electrical Generation (19 slides) • Concepts • Generation • Types of power plants	• Types of energy sources • Parts of power plants • Size and cost of generators
2nd 15' module	Electrical Transmission (13 slides) • Concepts • Transmission components • AC vs HVDC transmission	• Phase Angle • ROW • Network Structures/Resiliency
3rd 15' module	Distribution (15 slides) • Concepts • Step up/down voltage • 110 vs 220 V/ 50 vs 60 Hz	• Generator to consumer • Line losses • Smart meters
4th 15' module	Load Balancing (13 slides) • Concepts • Load Matching • Daily Peak Demand Reserve	• Grid Energy storage • Base load vs Peaking power plants • "Duck" curve

Figure 3b. Example of 15' lecture modules for a single day's lecture. Modules are designed to be readily convertible to on-line courses.

This work was the result of a summer faculty sabbatical funded by Sandia National Laboratories to S.G.

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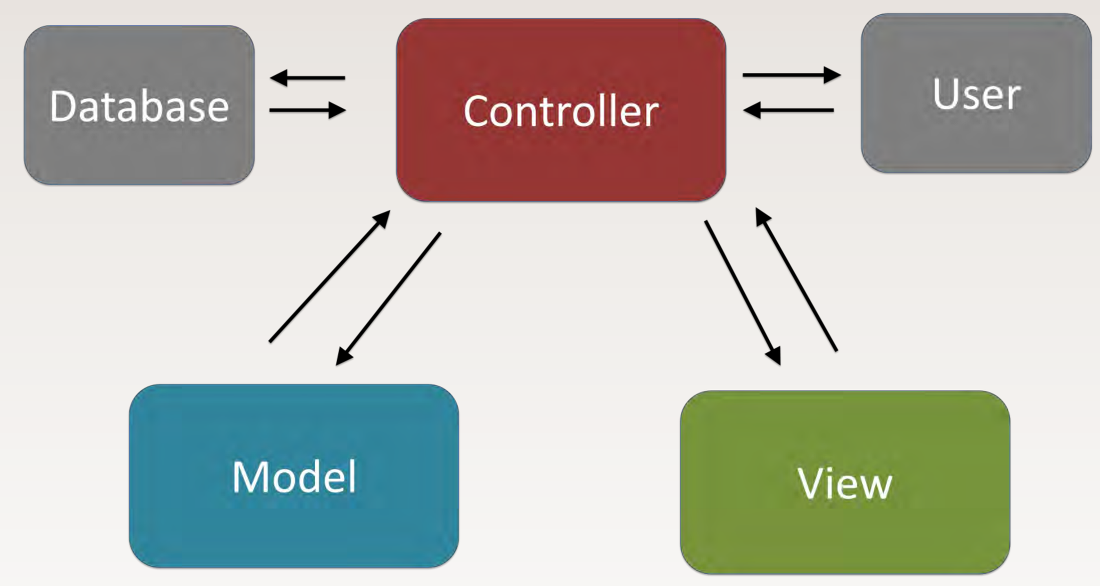
T. Ngo, J. Hernandez

Developing the Foundation and Next Phase of the Global Energy Storage Database

Database Development

- GESDB was developed using standard programming language Ruby on Rails with a PostgreSQL database
- The model-view-controller (MVC) framework provides structures for a database, web services, and web pages

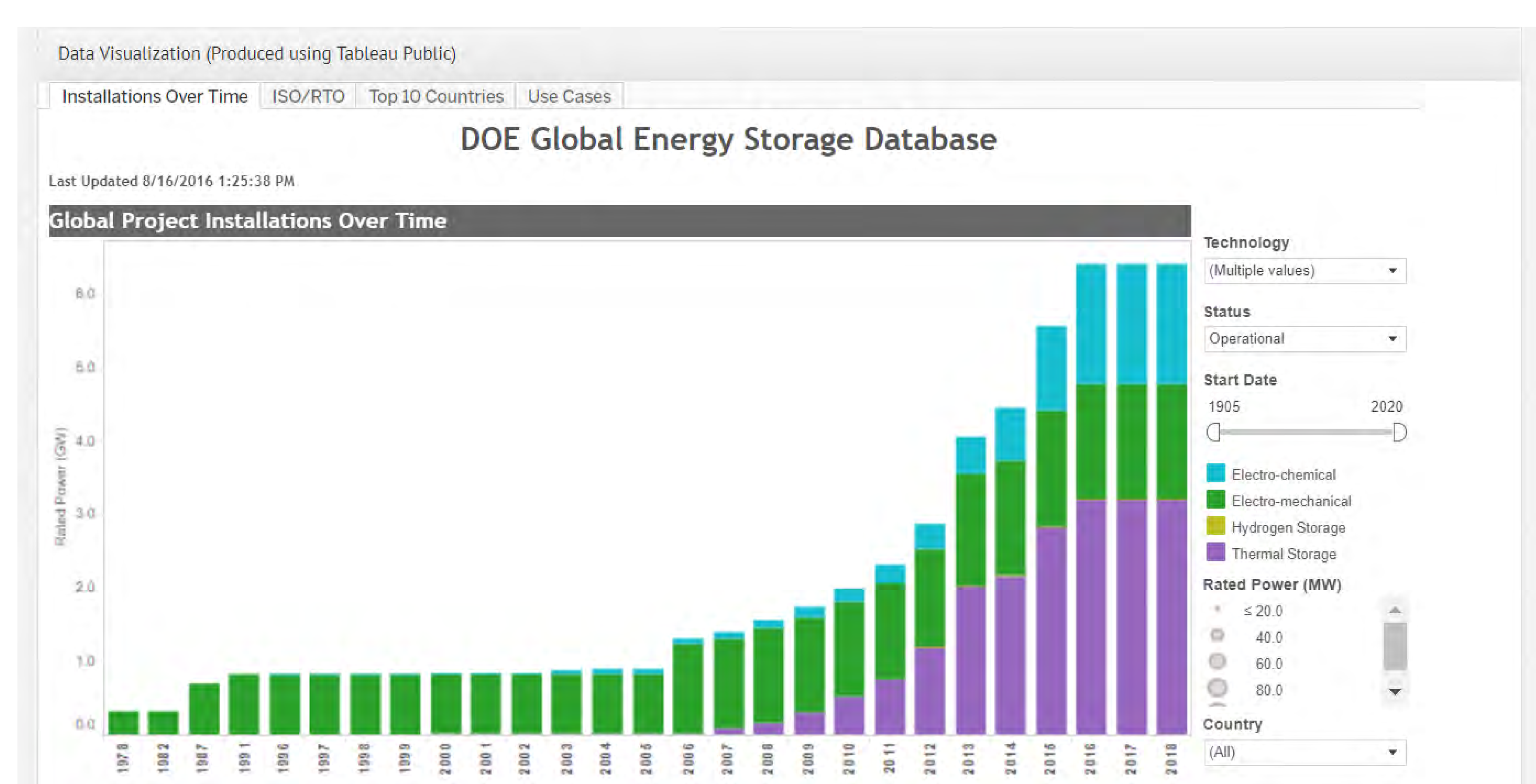


System Performance

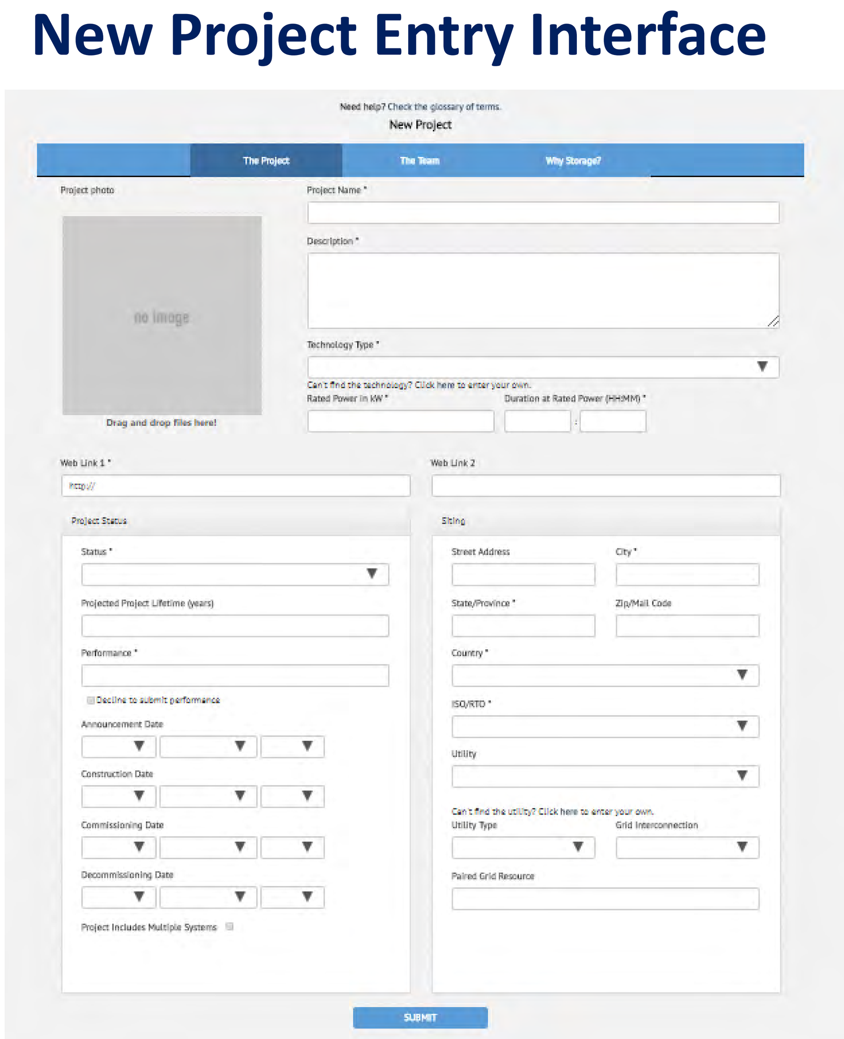
- 1600+ projects, 50+ technologies, 2 million page views

Next Phase Development

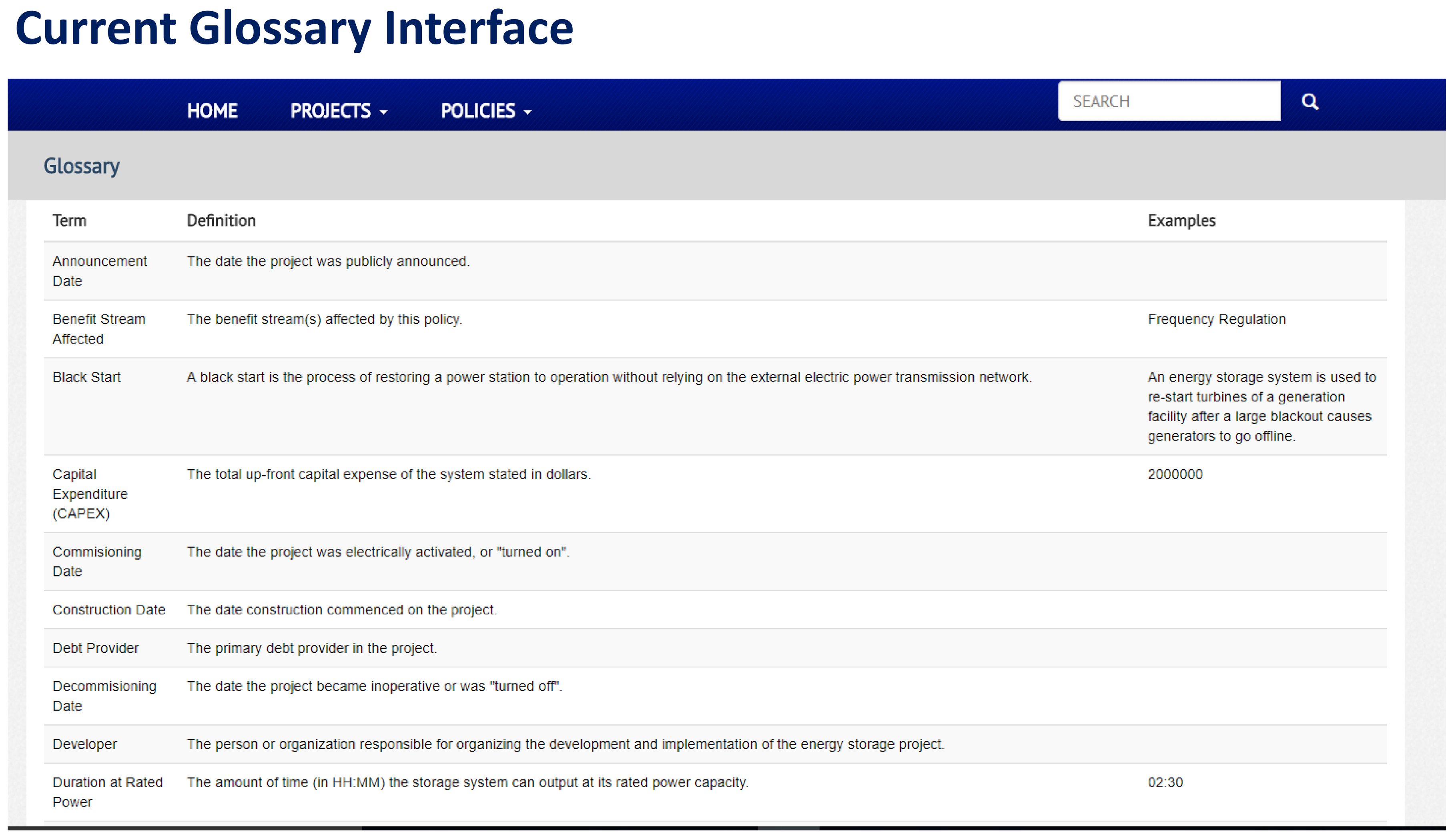
- New vetting process development to ensure reliable project details is present
- Changes to user interface to simplify user experience
- Promote new project entry interface so that more projects are entered by users/owners
- Create a more diverse user base and increase user engagement through social media/newsletter
- Establish more educational tools such as refining glossary, energy storage background, and videos
- Give user ability to select certain project fields to export to Excel or PDF



New Project Entry Interface



Current Glossary Interface



Term	Definition	Examples
Announcement Date	The date the project was publicly announced.	
Benefit Stream Affected	The benefit stream(s) affected by this policy.	Frequency Regulation
Black Start	A black start is the process of restoring a power station to operation without relying on the external electric power transmission network.	An energy storage system is used to re-start turbines of a generation facility after a large blackout causes generators to go offline.
Capital Expenditure (CAPEX)	The total up-front capital expense of the system stated in dollars.	2000000
Commisioning Date	The date the project was electrically activated, or "turned on".	
Construction Date	The date construction commenced on the project.	
Debt Provider	The primary debt provider in the project.	
Decommisioning Date	The date the project became inoperative or was "turned off".	
Developer	The person or organization responsible for organizing the development and implementation of the energy storage project.	
Duration at Rated Power	The amount of time (in HH:MM) the storage system can output at its rated power capacity.	02:30

We thank Dr. Imre Gyuk and the DOE Office of Electricity Energy Storage Program for funding this work.

Sandia National Laboratories

Maximizing the Cost-savings for TOU and NEM Customers Using Behind-the-meter Energy Storage

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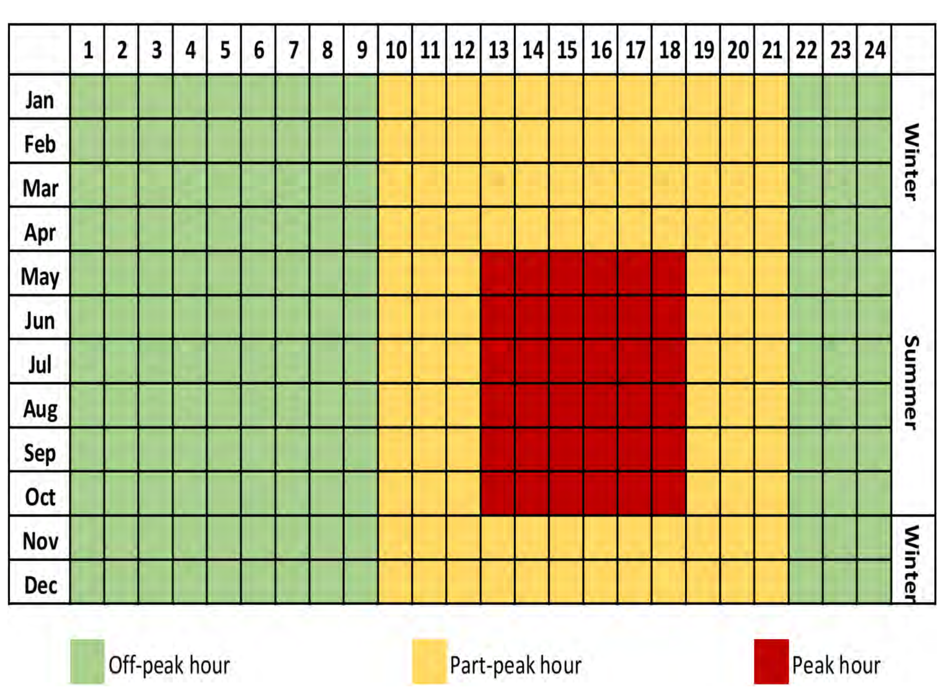
Email: tunguy@sandia.gov, rhbyrne@sandia.gov

Abstract

In this work, we provide an economic analysis of behind-the-meter (BTM) ESSs. A nonlinear optimization problem is formulated and then to transformed to Linear Programming (LP) problems using minmax technique. Case studies are conducted for PG&E's residential and commercial customers in San Francisco.

Time-of-use Pricing



- **Time schedule for TOU:**
  Hour: peak hours, part-peak hours and off-peak hours.
  Day: regular week days, weekend days and holidays.
  Month: summer months and winter months.

E-19 SCHEDULE'S TOU RATES

	Summer	Winter
Off-peak energy	0.08651 \$/kWh	0.09317 \$/kWh
Part-peak energy	0.11333 \$/kWh	0.10779 \$/kWh
Peak energy	0.15384 \$/kWh	-
Part-peak demand	5.18 \$/kW	0.12 \$/kW
Peak demand	18.64 \$/kW	-
Maximum demand	16.08 \$/kW	16.08 \$/kW

- **Energy and demand prices** are time dependent

Net-metering Program

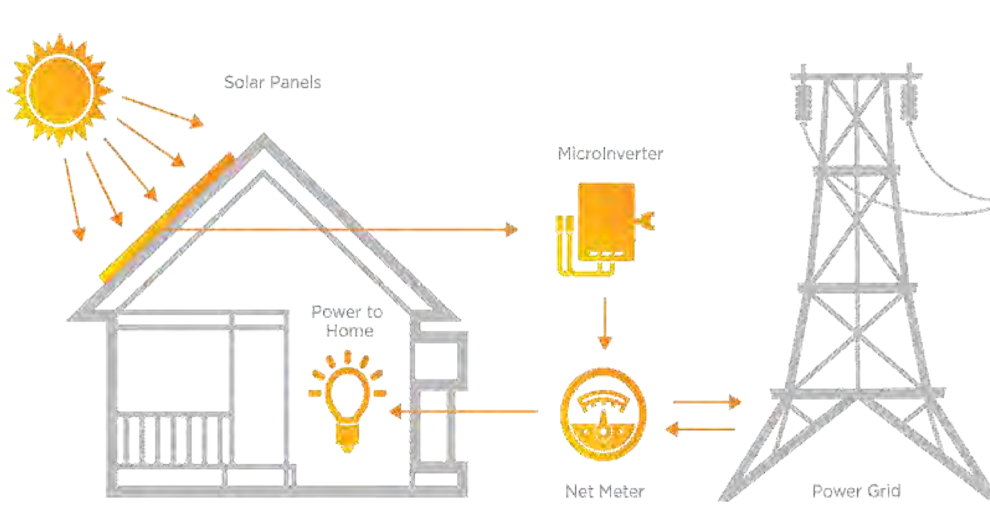


Image Credit - *Lowcountry Solar*

- **Net metering (NEM)** programs allow customers who own renewable energy systems to export their excess energy to the grid.

Energy Storage for TOU and NEM Customers

- **TOU customers** could benefit by charging their ESSs during off-peak hours and then discharging them during peak.
- **NEM customers** can increase their savings by storing the excess renewable energy when the load is low and use that energy later when the load is high.

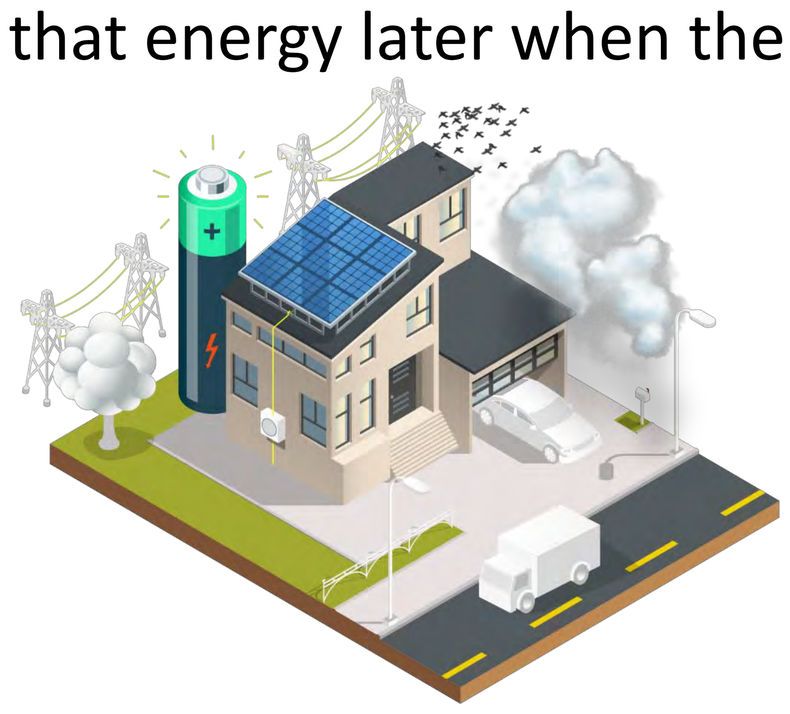


Image Credit - *Landisgyr*

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Minimizing Electricity Bills for TOU & NEM Customers

Therefore, to justify the deployments of ESSs for BTM applications, it is essential to optimize storage operation and size to maximize the overall benefits for the customers

$$\min\{\mathrm{C}^{\mathrm{m}}_{\mathrm{E}} + \mathrm{C}^{\mathrm{m}}_{\mathrm{N}} + \mathrm{C}^{\mathrm{m}}_{\mathrm{D}}\} \tag{1}$$

s.t. energy storage constraints, where

$$\mathrm{C}^{\mathrm{m}}_{\mathrm{E}} = \sum_{i\in \mathrm{H}^{\mathrm{m}}} \alpha_i q_i^{\mathrm{net}} \mathrm{P}_i \tag{2}$$

$$\mathrm{C}^{\mathrm{m}}_{\mathrm{N}} = \sum_{i\in \mathrm{H}^{\mathrm{m}}} (1-\alpha_i) q_i^{\mathrm{net}} \mathrm{P}^{\mathrm{s}}_i \tag{3}$$

$$\mathrm{C}^{\mathrm{m}}_{\mathrm{D}} = \max_{i\in \mathrm{H}^{\mathrm{m}}}\{q_i^{\mathrm{net}}\}\mathrm{D}^{\mathrm{m}}_{\max} + \max_{j\in \mathrm{H}^{\mathrm{m}}_{\mathrm{pk}}}\{q_j^{\mathrm{net}}\}\mathrm{D}^{\mathrm{m}}_{\mathrm{pk}} + \max_{k\in \mathrm{H}^{\mathrm{m}}_{\mathrm{ppk}}}\{q_k^{\mathrm{net}}\}\mathrm{D}^{\mathrm{m}}_{\mathrm{ppk}} \tag{4}$$

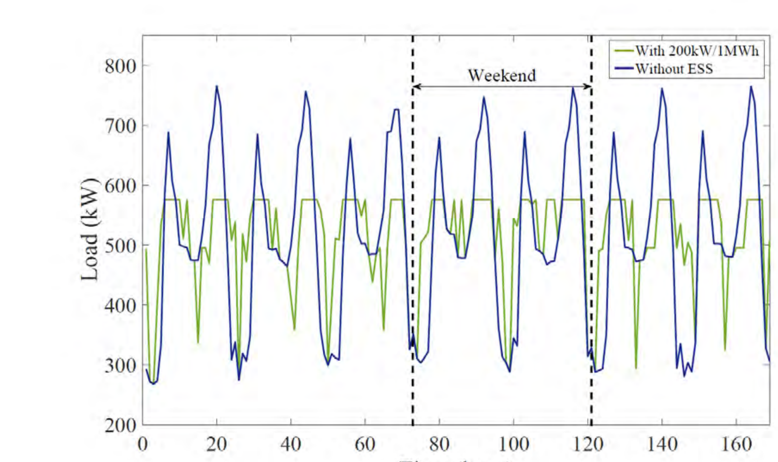
with $q_i^{\mathrm{net}} = q_i^{\mathrm{ld}} - q_i^{\mathrm{re}} + q_i^{\mathrm{c}} - q_i^{\mathrm{d}}$ and α_i ($\forall i \in \mathrm{H}^{\mathrm{m}}$) is binary and defined as follows:

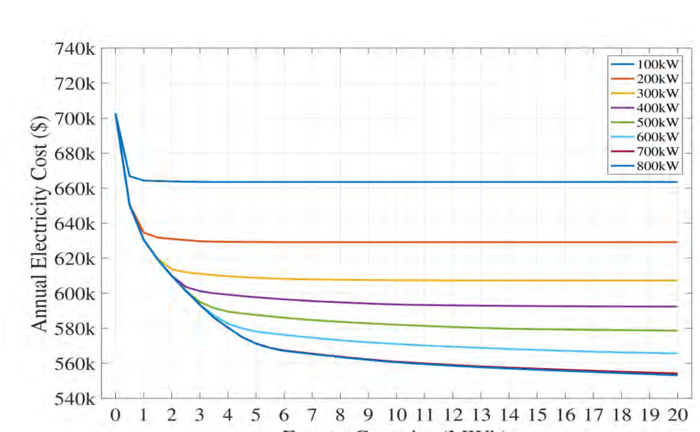
$$\alpha_i = \begin{cases} 1 & \text{if } q_i^{\mathrm{net}} \geq 0 \\ 0 & \text{otherwise} \end{cases} \tag{5}$$

Case Studies

Case studies: conducted for PG&E's customers in San Francisco.

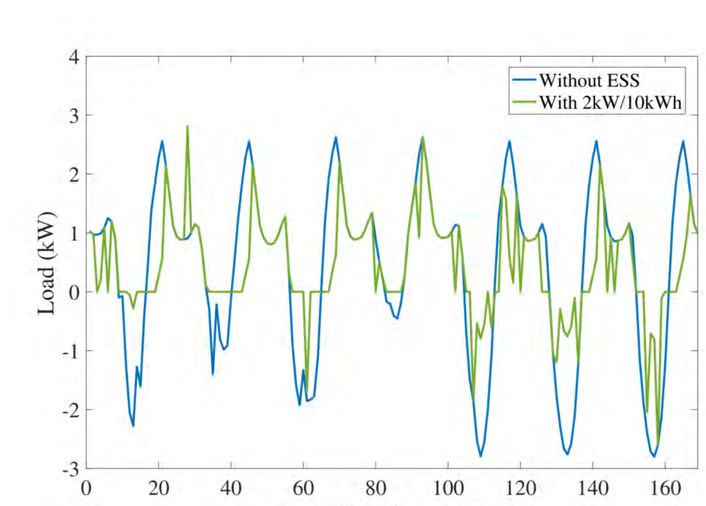
Results – TOU Commercial Customers:

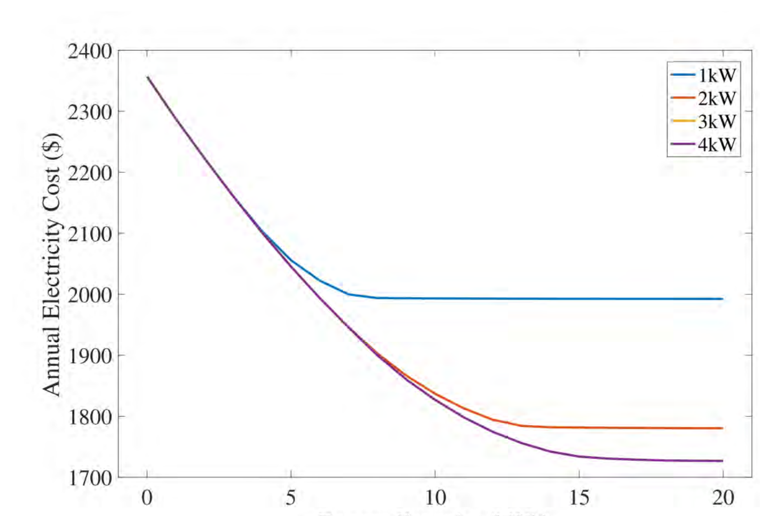




- Better savings for summer
- Significantly shave the peak
- Higher charge during wk
- Larger ES size, better saving.

Results – NEM & TOU Residential Customers:





Conclusions

- An optimization problem is formulated to minimize the monthly electricity bill of TOU and NEM customers.
- Future work in this area would analyze the impact of BTM energy storage to the reliability and resiliency of distribution networks.

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Incorporating Non-linear Energy Flow Models in Revenue Maximization for Energy Storage

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Abstract

Techno-economic analyses of energy storage currently use constant-efficiency energy flow models. In practice, (dis)charge efficiency of energy storage varies as a function of state-of-charge, temperature, (dis)charge power. Therefore, using the constant-efficiency energy flow models will cause suboptimal results. This work focuses on incorporating non-linear energy flow models based on non-linear efficiency models in the revenue maximization problem of energy storage.

Energy Flow Model of Energy Storage

Energy flow models capture the energy flow, taking into account losses from energy conversion and storage self-discharge.

- **Energy flow model with constant efficiencies:**

$$S_t = \gamma_s S_{t-1} + (\gamma_c p_t^c - p_t^d / \gamma_d)\Delta_t$$

S_t: Internal energy capacity at time i

γ_s: Efficiency due to self-discharge

γ_c: Constant charge efficiency

γ_d: Constant discharge efficiency

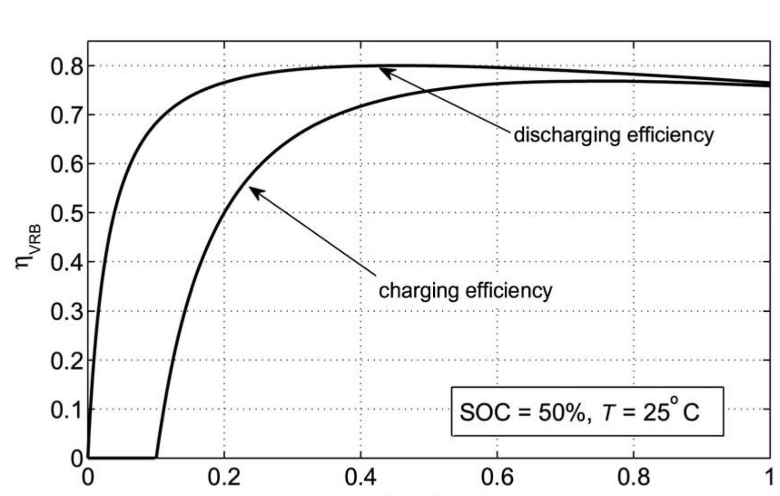
- **Energy flow model with efficiency functions :**

$$S_t = \gamma_s S_{t-1} + (p_t^c \gamma_c(p_t^c, T, S_{t-1}) - p_t / \gamma_d(p_t^d, T, S_{t-1}))\Delta_t$$

$\gamma_c(p_t^c, T, S_{t-1})$: Non-linear charge efficiency function

$\gamma_d(p_t^d, T, S_{t-1})$: Non-linear discharge efficiency fucntion

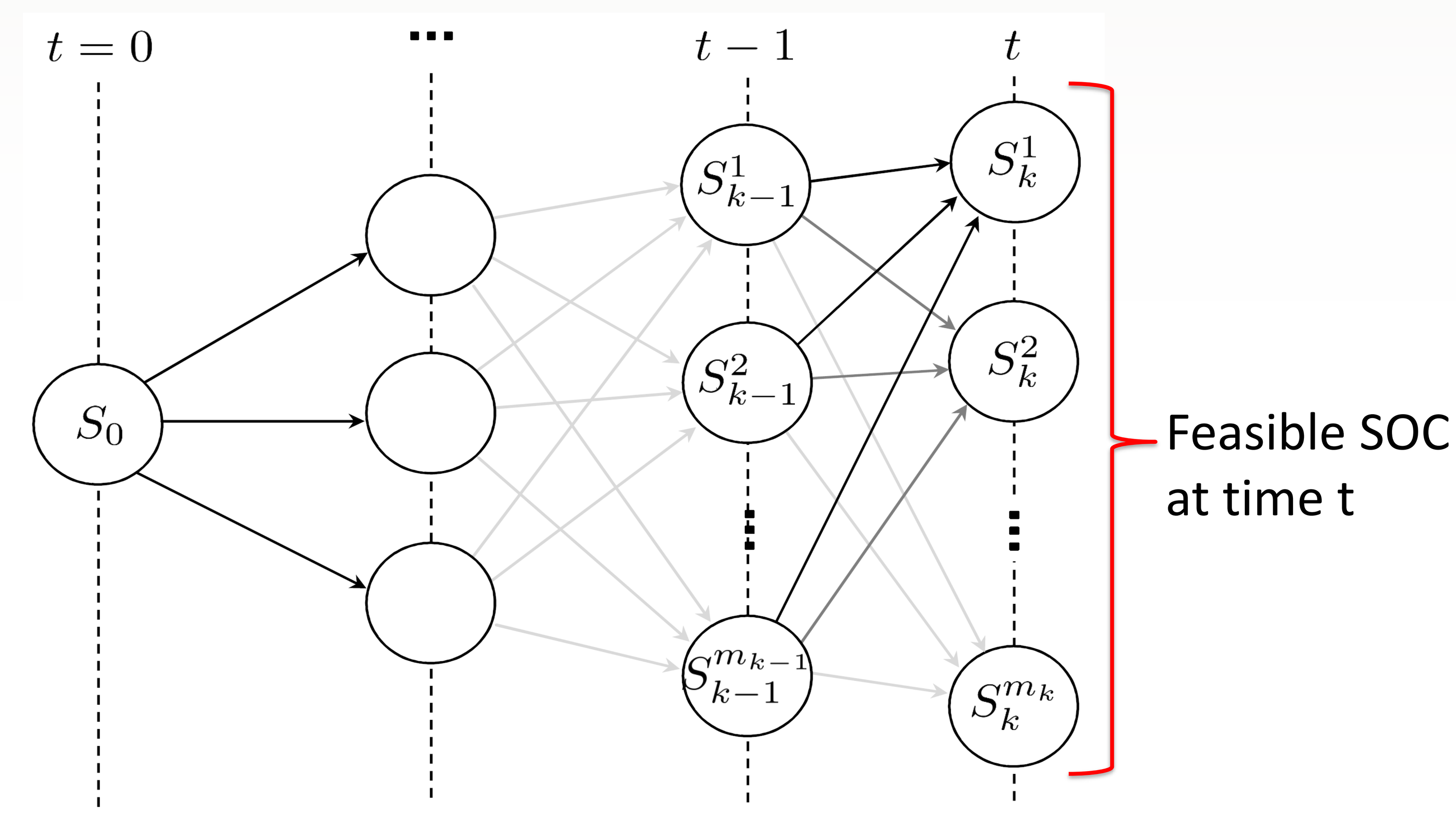
- **Non-linear efficiency functions:** charge and discharge efficiencies are non-linear functions of SOC, T, P.



Challenges of Incorporating Non-linear Energy Flow Model

- **Non-convexity:** the revenue optimization problems become non-convex due to non-convex constraints.
- **Complex dynamics:** the state of charge is now a non-linear functions of multiple variables.
- **Expensive linearization:** the non-linearity state-of-charge model can be linearized but introducing a large number of binary variables

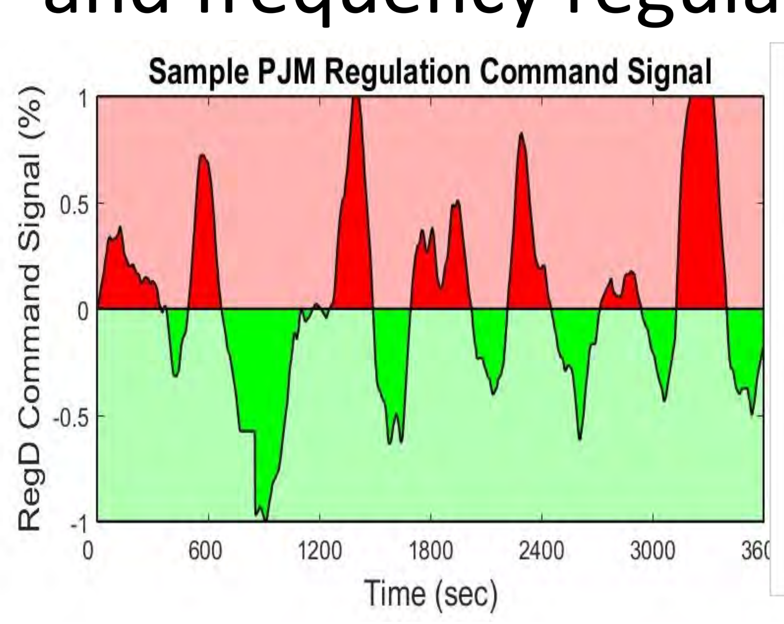
Dynamic Programming Approach

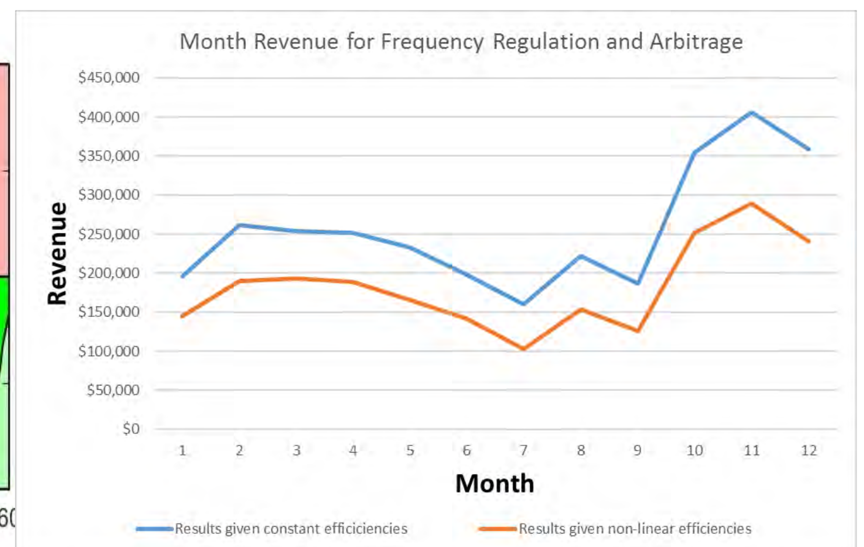


- **Algorithm:**
  - Define the nodes: define feasible SOC at t
  - Find (t-1,t) links: find policies that maximize $.
  - Find max sub-paths: memorize the state at t-1 that results in max $ at t
  - Find the solution: trace backward to find the solution.

Results

- **Case study:** 20MW/5MWh VRB for arbitrage and frequency regulation in PJM





- **Observations:**
  - Revenue estimation using non-linear efficiencies is **~30% lower** in comparison with that when using constant efficiencies. This is because the non-linear model can capture the low-efficient operations when following regulation signals.
  - The DP computing time is polynomial to the number of time steps and exponential to the number of states.

Future Work

- Applying the non-linear energy model and DP approach in revenue evaluation of ES in different market areas.
- Incorporating the uncertainties of forecast data into the optimization problem.

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Accelerating Electrolyte Design Process

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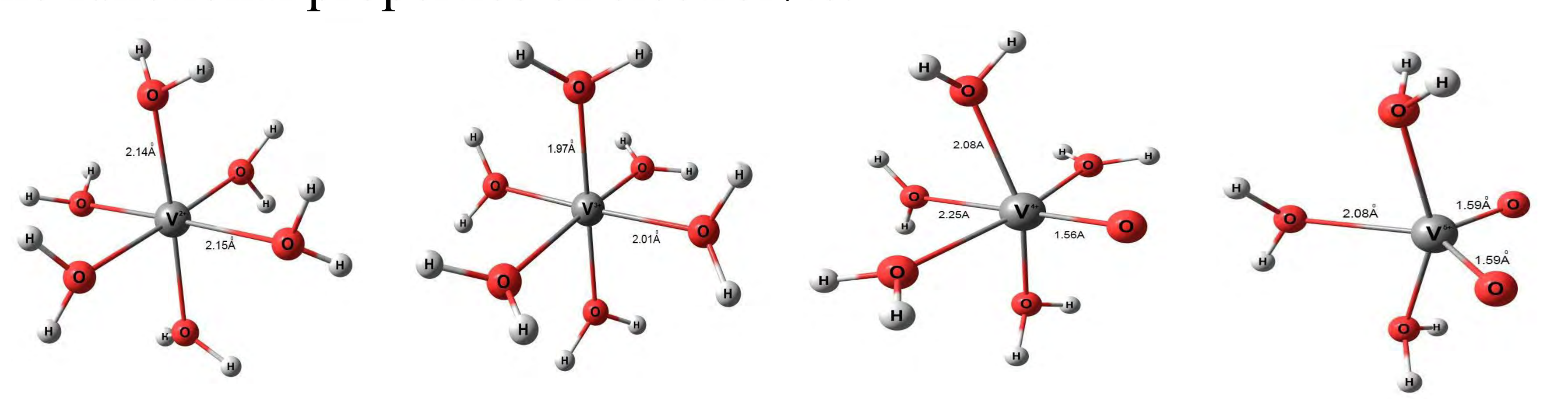
Objectives:

Ability to predict the solubility, stability, redox potential and overall performance of redox flow battery electrolytes

Develop screening procedure using combined computational and experimental methods to evaluate and identify the optimal solvents, additives and redox active molecules

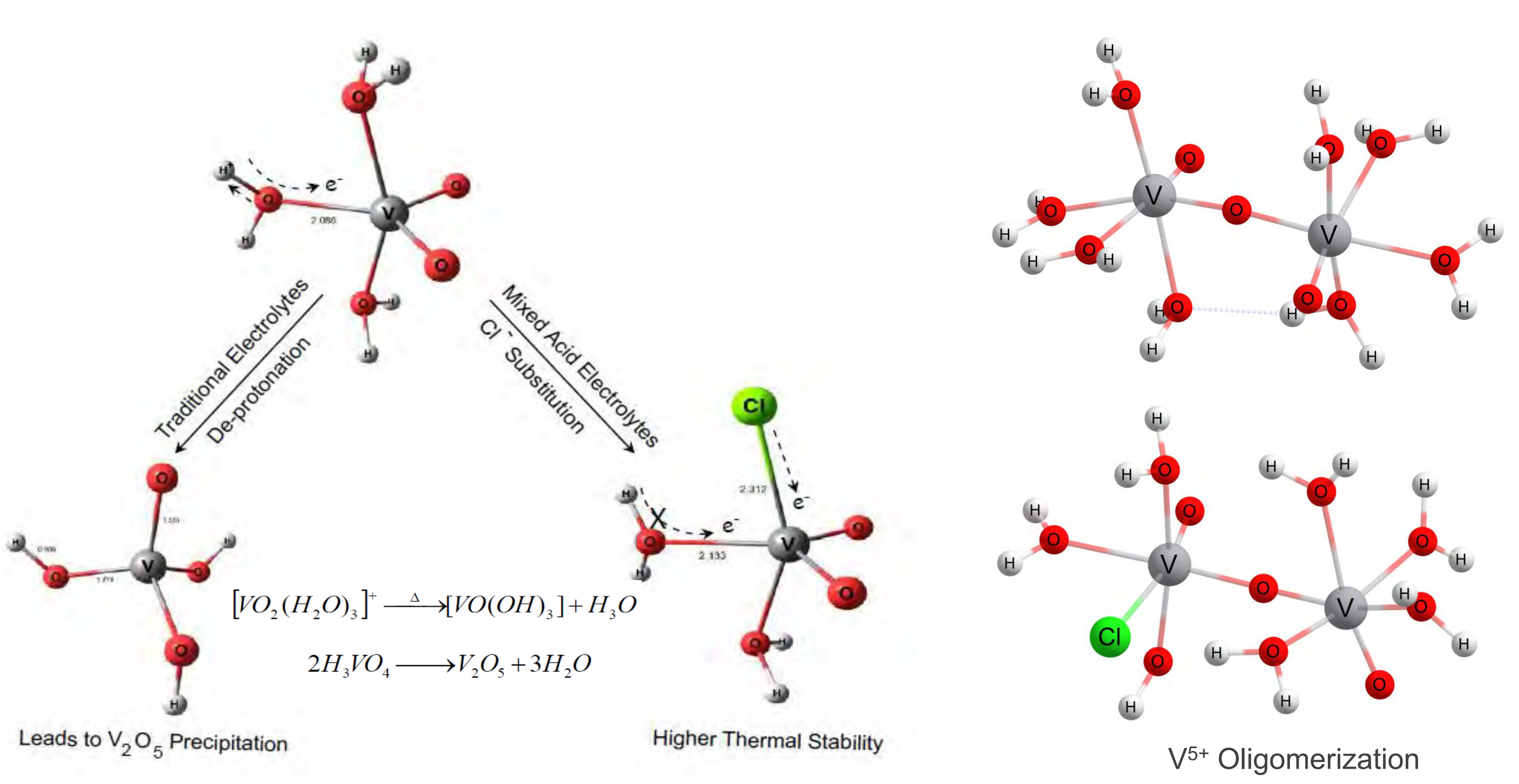
Designing vanadium based electrolytes:

Vanadium solvation structure and ligand exchange dynamics dictates the functional properties of electrolvte.

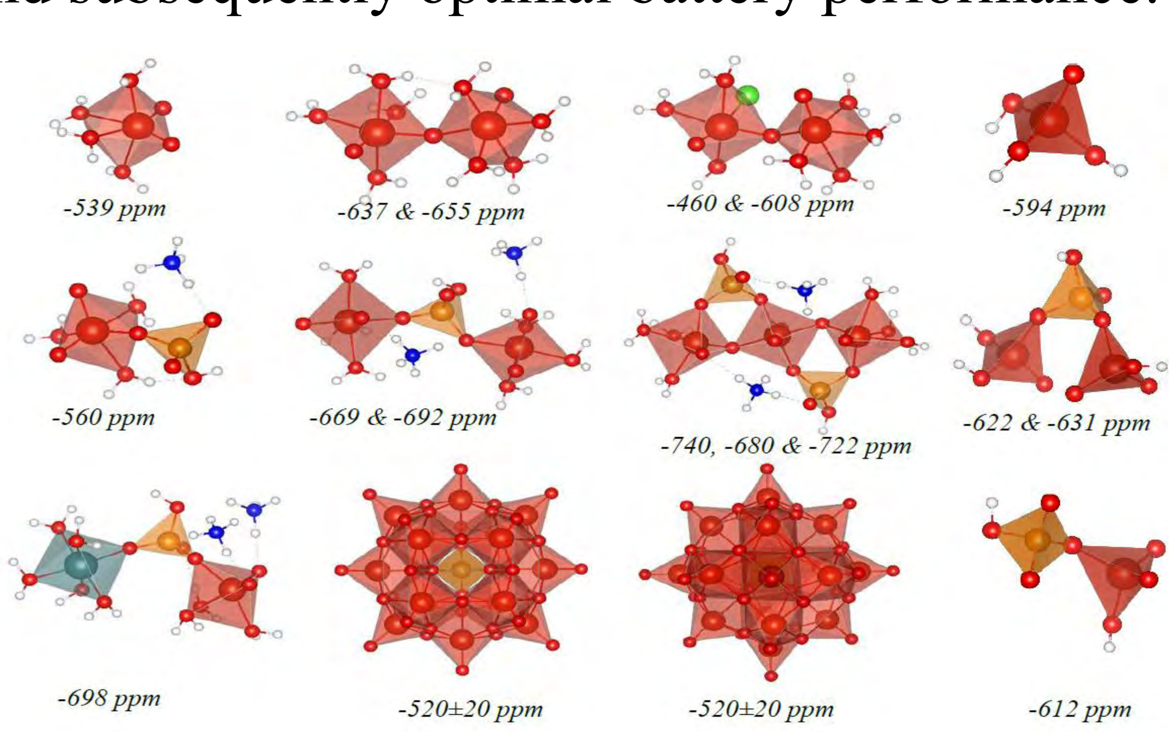


$[V.6H_2O]^{+2}$ $[V.6H_2O]^{+3}$ $[VO.5H_2O]^{+2}$ $[VO_2.2H_2O]^{+1}$

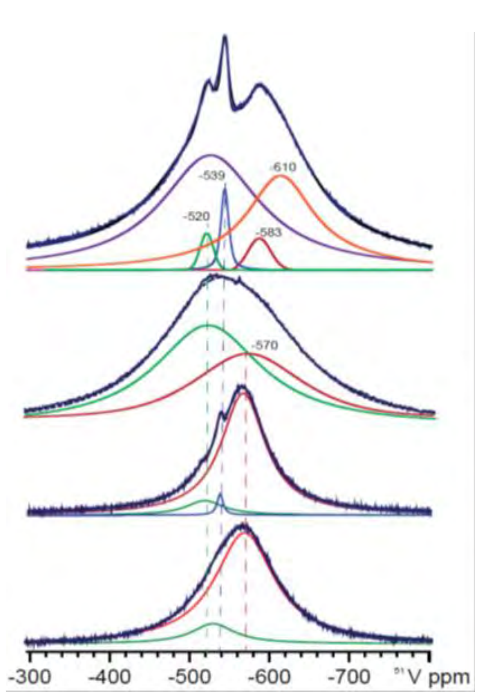
Designing mixed acid flow battery electrolyte through inhibiting deprotonation reaction of V^{5+} solvation with chloride substitution.



Designing bi-additives that can enable precise tuning of ion solvation and subsequently optimal battery performance.

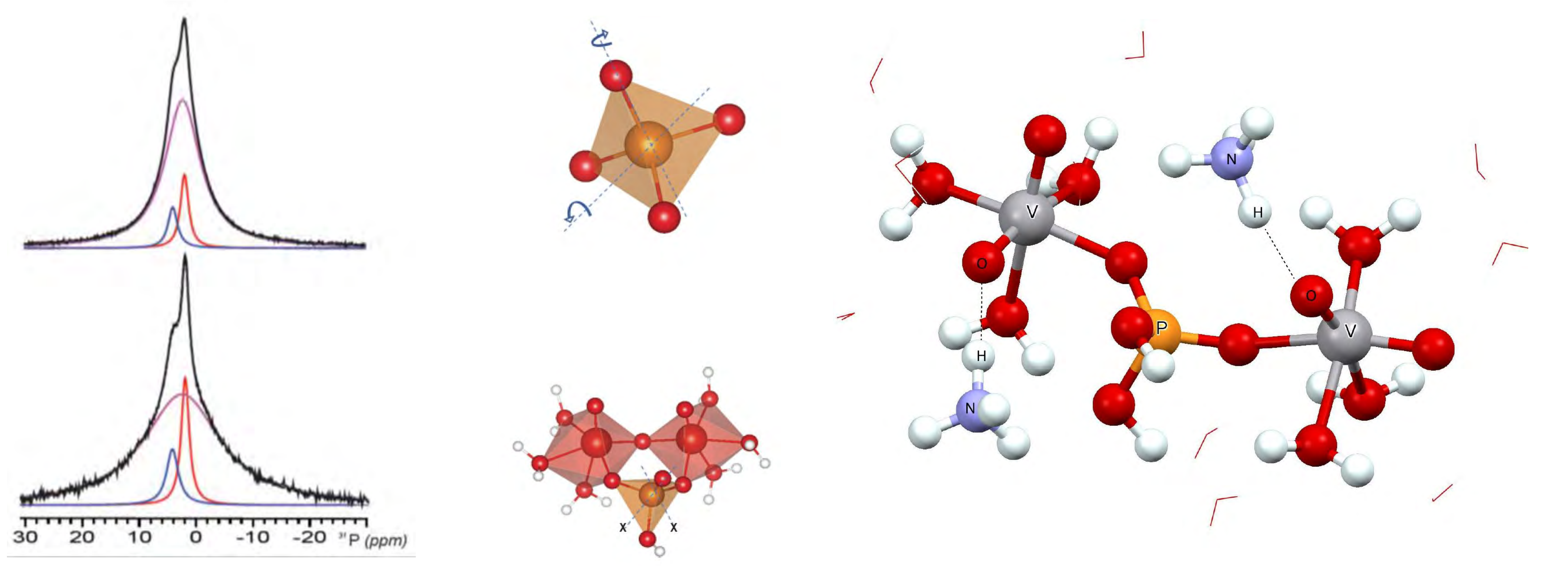


Tuning V^{5+} solvation – Bi-additives



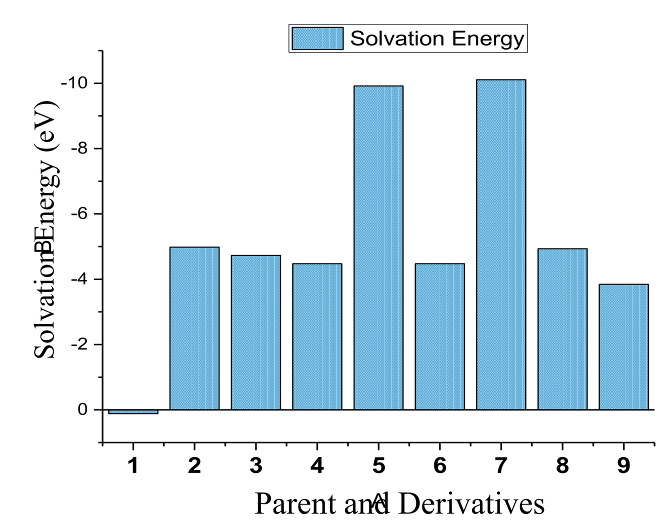
^{51}V NMR

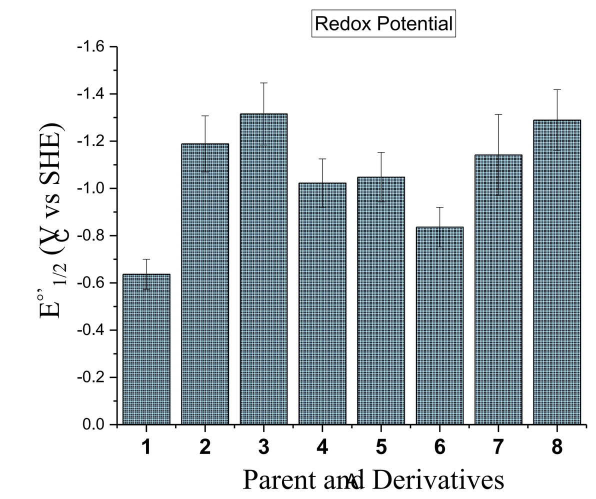
Composition of additive system is critical, as it dictates the rotational and translational ion dynamics and subsequently solubility and viscosity .



^{31}P NMR Phosphate rotation Preferential solvation of NH_4^+

Designing organic-aqueous electrolytes:

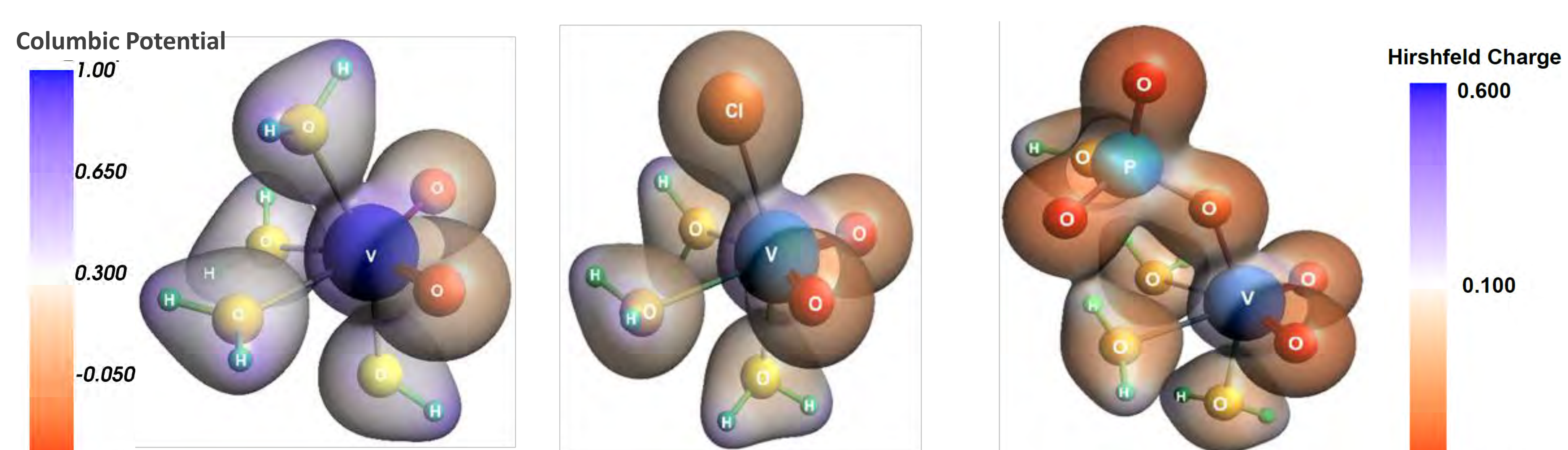




Density functional theory (DFT) based computational screening method is adopted to design optimal functional groups by predicting the solubility and redox potential of organic redox molecules.

Summary and Perspective:

Ion solvation study reveals, thermally activated precipitation of V^{5+} electrolyte can be suppressed through inhibiting deprotonation process and/or perturbing the formation of higher order oligomers.



$[VO_2.2H_2O]^{+1}$ $[VO_2.Cl.\ 3H_2O]^{+1}$ $[VO_2.PO_4.\ 3H_2O]^{-2}$

Adopting asymmetric molecular structure and charge distribution within redox molecule through addition of functional groups can significantly enhance the solubility of organic redox molecules . A vigorous DFT based screening procedure is developed for optimal electrolyte design.

Acknowledgements

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4. Nature communications 6, 6303, **2015.**
5. ChemPlusChem 80 (2), 428-437, **2015**.

Diagnostics of Capacity Fading Mechanisms in Aqueous Soluble Organic (ASO)-Based Flow Batteries

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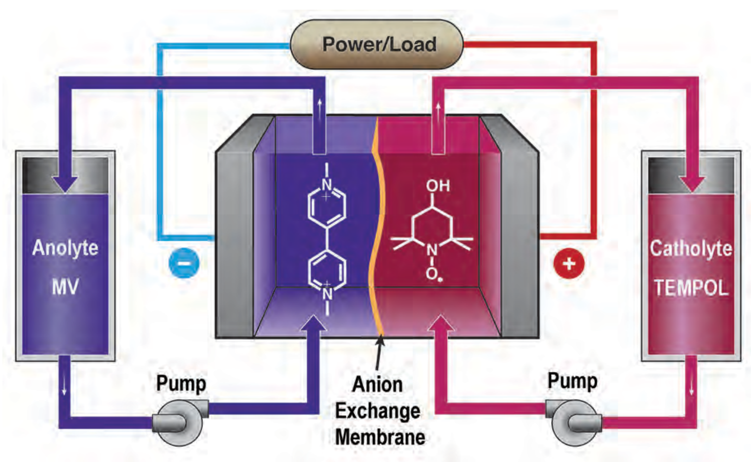
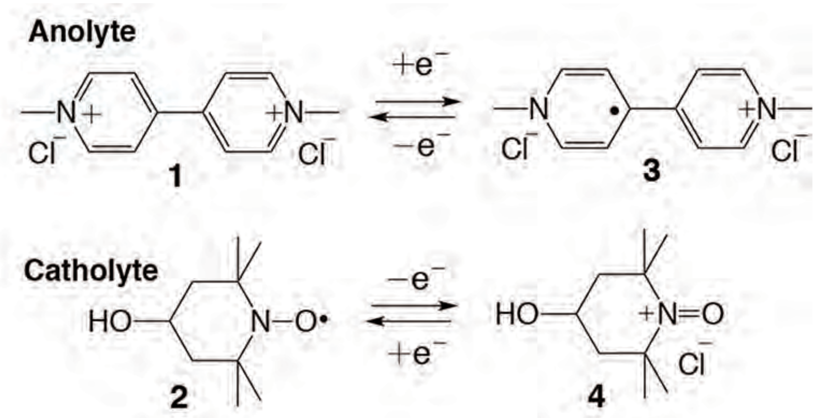
Introduction: To address the challenge of high vanadium cost, aqueous soluble organic (ASO) molecules are investigated as cost-effective redox-active alternatives for flow batteries.[1] We developed a MV/TEMPOL system favorably with high solubility (>2M) and low cost (<$7/kg).[2] However, capacity decay was observed at high ASO concentrations, which also existed in many other ASO systems.



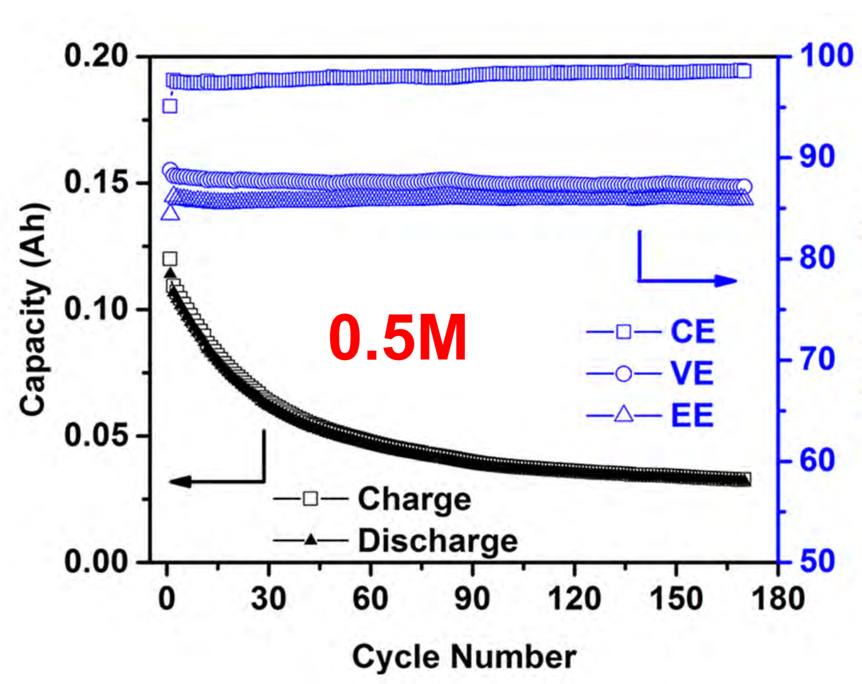


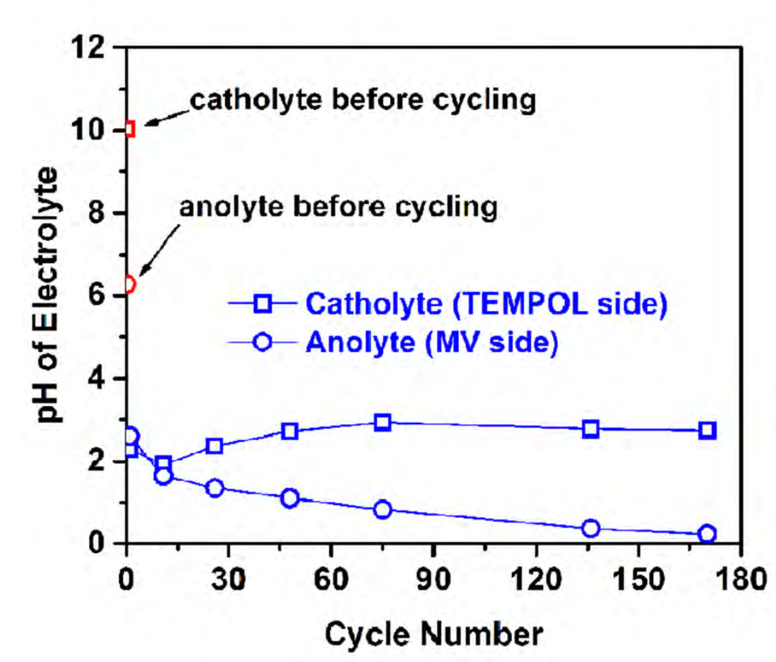
Objectives: Using the MV/TEMPOL system as a platform, this research aims to explore the generic strategies to study the basic science of structure-stability relationships in ASO materials. We show how the acquired understandings can provide guidance for rational materials design to harvest improved cycling stability in flow cells.

Results and Discussion

➢ **Experimental Observations of the MV/TEMPOL Flow Cells**

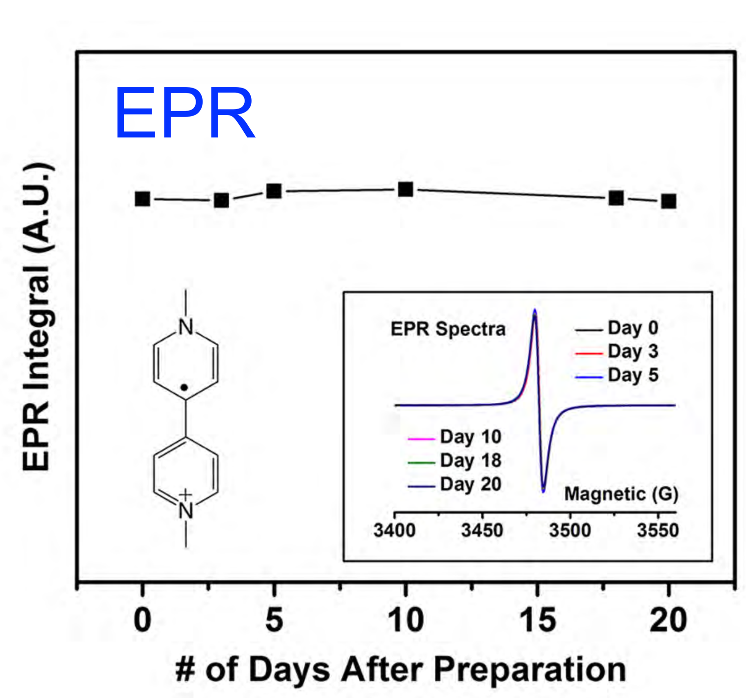
- Continuous capacity fading
- Significant decrease in pH

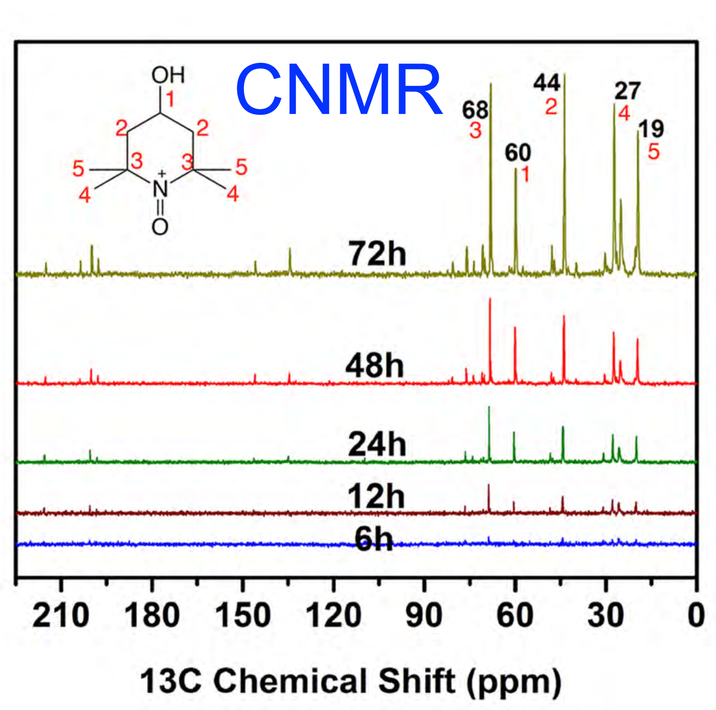




➢ **Chemical Diagnostics of Charged ASO Species**

- Stable $MV^{+•}$ (**3**)
- Unstable $TEMPOL^{+}$ (**4**)



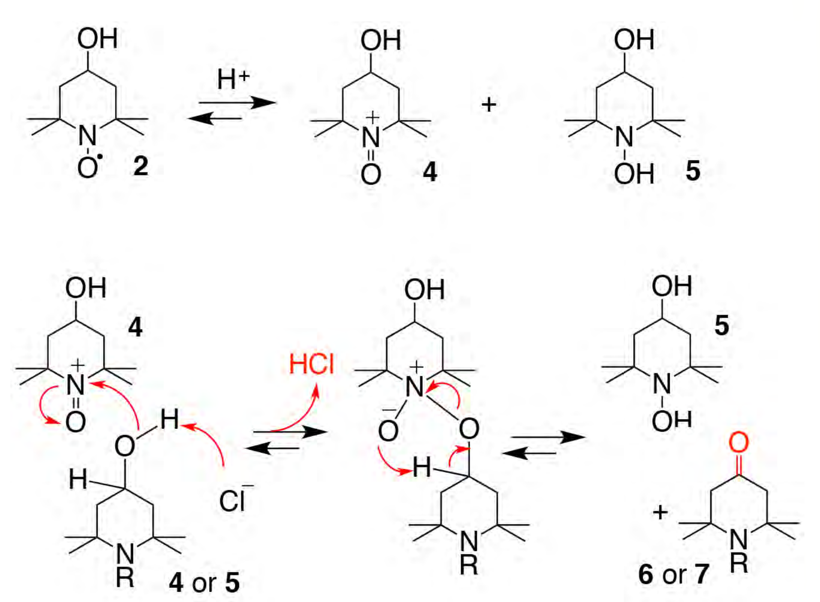


- Possible Degradation Pathways of $TEMPOL^{+}$ (**4**)

(1) +N=O can oxidize C-OH to form C=O (i.e., ^{13}CNMR peaks at >200 ppm).

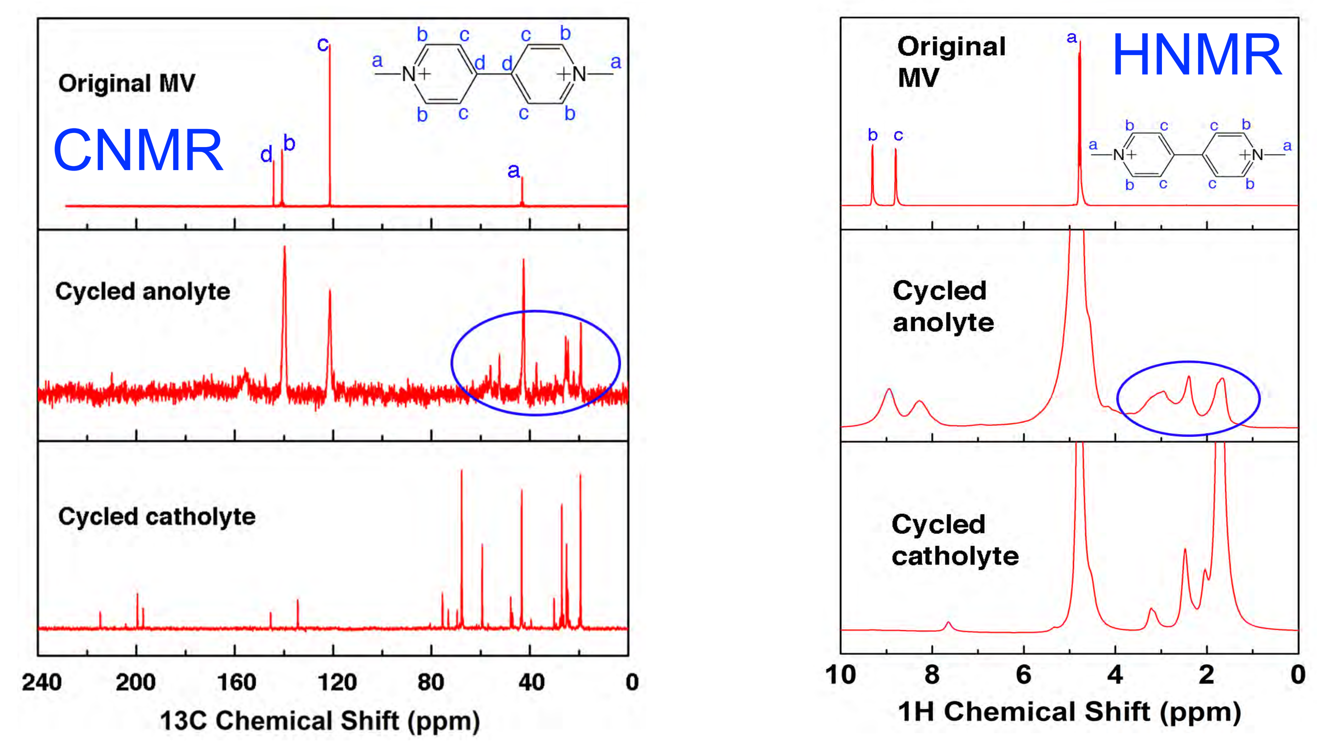
(2) Both nitroxide radical (**2**) and $MV^{+•}$ (**3**) are unstable in acid.

(3) Multiple TEMPO species present, explaining the complex NMR patterns.



➢ **Chemical Diagnostics of Cycled ASO Species**

- Crossover of TEMPOL species (NMR peaks observed in galvanostatically cycled anolyte – highlighted by blue circles)
- No MV peaks observed in cycled catholyte

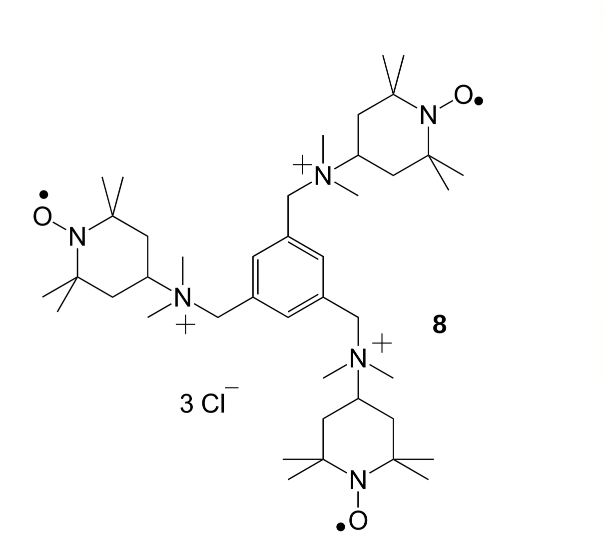


Summary and Perspective

- Complementary resonance spectroscopies (NMR and EPR) are standard approaches to investigate materials evolution and performance decay mechanisms in ASO-based flow batteries.
- In the MV/TEMPOL system, parasitic side reactions and crossover of TEMPO species are the major reasons for capacity decay.
- This understanding can guide rational design of stable TEMPO derivatives by blocking the decay pathways.

Future Work

- Synthesis and testing of TEMPO oligomers: (i) no –OH group to eliminate side reactions; (ii) bulky size with multiple cations to reduce crossover.



Acknowledgements

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1. X. Wei, W. Pan, W. Duan, A. Hollas, Z. Yang, B. Li, Z. Nie, J. Liu, D. Reed, W. Wang, V. Sprenkle, Materials and Systems for Organic Redox Flow Batteries: Status and Challenges. *ACS Energy Letters* **2017**, *2*, 2187.
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High Temperature Optocoupler for 3D High Density Power Module

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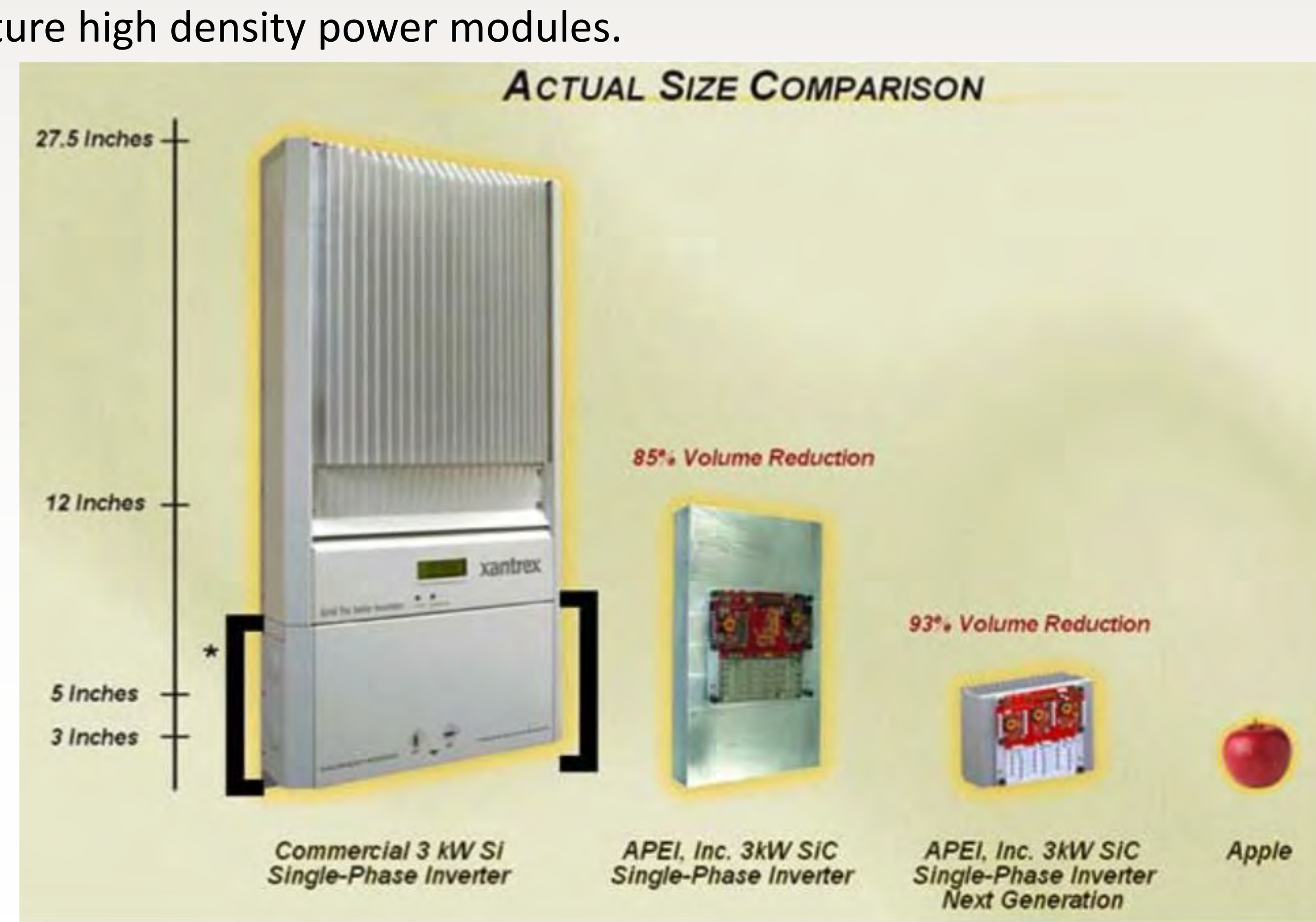
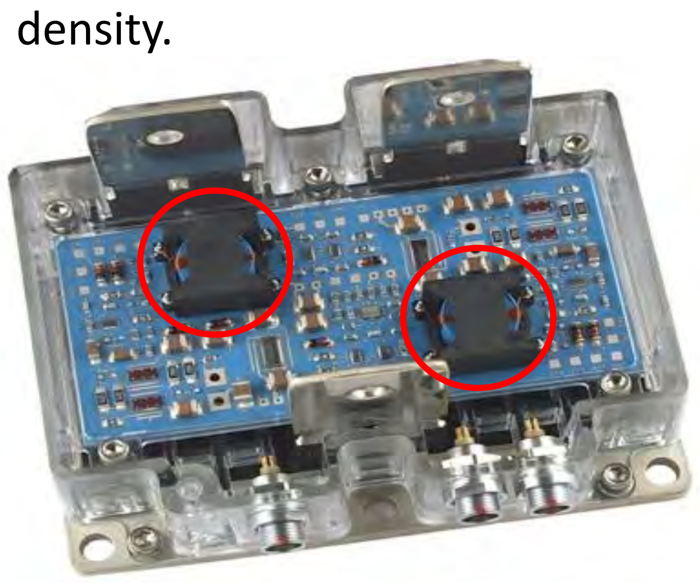
Stanley Atcitty, Robert Kaplar, Sandia National Laboratories

Motivation

Future energy storage system will continuously drive the demand for power modules. Power modules are the core components of all power electronics systems, which convert electrical energy from one form into another. They are required to convert energy from renewable sources (i.e., solar panels or wind turbines), and provide power for a wide variety of electronics and electronic systems (e.g., DC power supplies and inverters). The conventional power modules require a comprehensive thermal management system, which inevitably adds weight and cost. **High temperature high density power modules** will not only enhance reliability but also substantially reduce cooling requirements. The total system cost and weight are significantly decreased. The picture below shows an example of scaling on a single-phase inverter due to the integration of the high temperature high density power modules.



Enabled with advanced 3D integration and packaging technologies, integrated high density power module solutions can achieve much more superior performance over the conventional discrete solutions in terms of efficiency, thermal management and power density.



In 2009, the University of Arkansas, along with Arkansas Power Electronics Inc. (APEI, now Wolfspeed), Rohm Inc., and Sandia National Laboratory, won an R&D 100 award for the world's first Silicon Carbide (SiC) based vehicular inverter drive that is capable of continuous operation at 250°C. For this award-winning power module, multiple **bulky gate transformers** (red circled) used as a galvanic isolation system to float the high voltage gate driver **limit further size reduction of the power module.**

An integrated high temperature optocoupler (i.e., packaged light emitter and detector) is therefore highly desirable in order to facilitate the continuous scale-down of gate driver circuitry that will lead to 3D ultra high density integrated power modules and achieve disruptive performance in terms of thermal management, power density, power efficiency, reliability and operating environments.

Objective

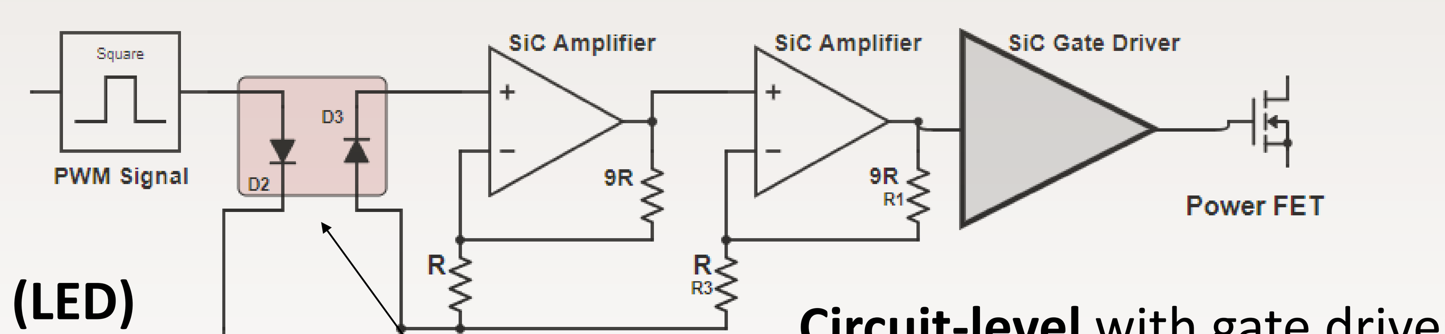
Develop a reliable high-temperature optocoupler to replace gate transformers as a galvanic isolation system. It can operate at 250°C and above with at least ten-year projected lifetime, which has over 500 times volume reduction from gate transformer.

Type of Isolations	Coupling Method	Size & weight	Signal Modulating	CMTI	Response Time	Isolation	EMI /ESD
Gate transformer	Magnetic	Bulky, heavy	Needed	Low	Fast	High	Average
Digital isolation	Capacitive	Small, light	Needed	Medium	Medium	Medium	Average
Opto-coupler	Optical	Small, light	Not Needed	High	Medium	High	Good

Methods

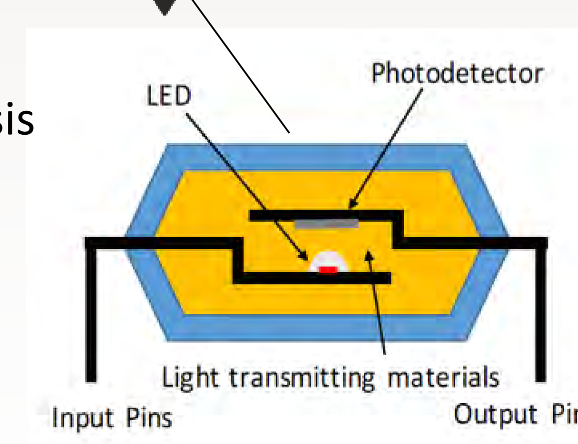
Challenges at high temperatures for optocouplers
- LED material quantum efficiency drops
- LED device and packaging degradation
- Detector responsivity drops
- Detector dark current increases
- Output signal-to-noise ratio drops
- Others (bandwidth, long-term reliability, etc)

Our approaches
- From optoelectronic materials to components (bottom up)
- From gate driver circuit to LED and detector device (top down)



Material-level (LED)
- Quantum efficiency
- PL intensity
- Power dependent analysis

Device-level (LED)
- Light intensity
- Quantum efficiency
- Injected current
- long-term reliability



Circuit-level with gate driver
- SNR requirements
- HT amplifier
- HT gate driver

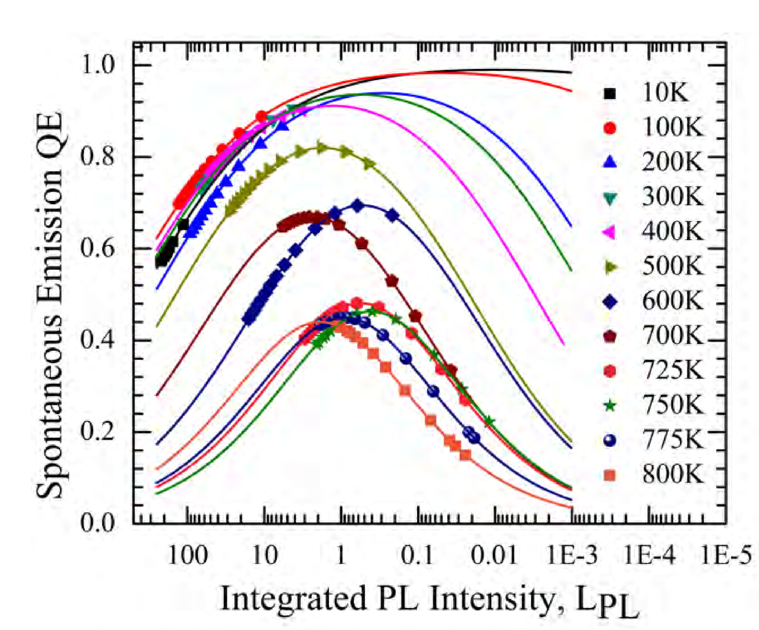
Device-level (Detector)
- Responsivity
- Leakage current
- Signal to noise (SNR) ratio

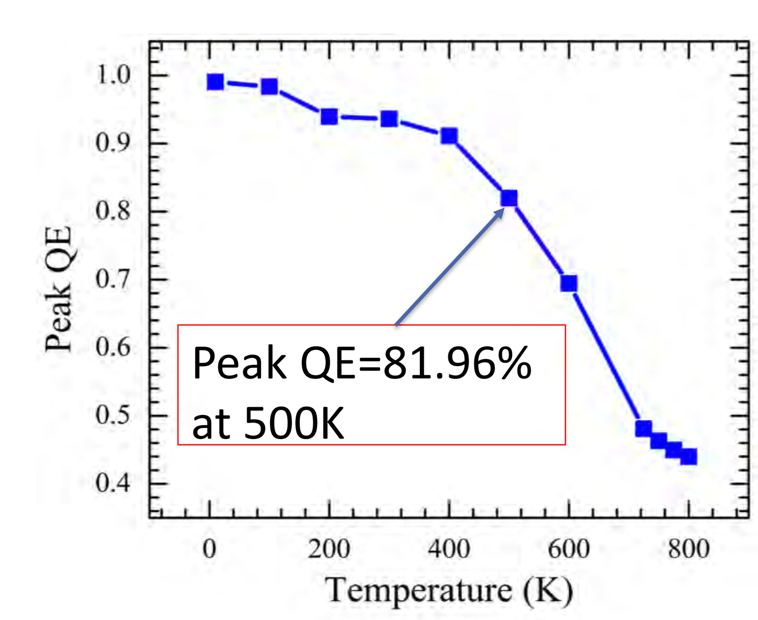
Component-level (optocoupler)
- Bandwidth
- Isolation voltage
- Propagation delay

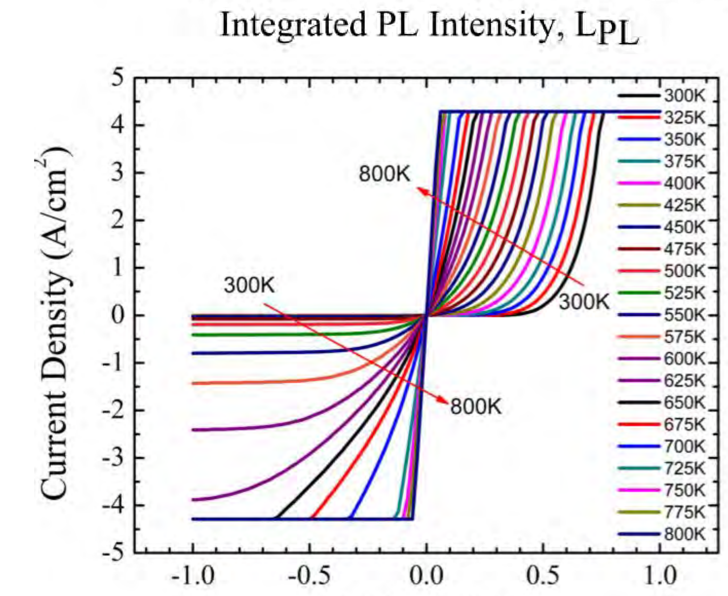
Component-level (packaging)
- Device architecture
- HT insulation materials
- Dielectric properties

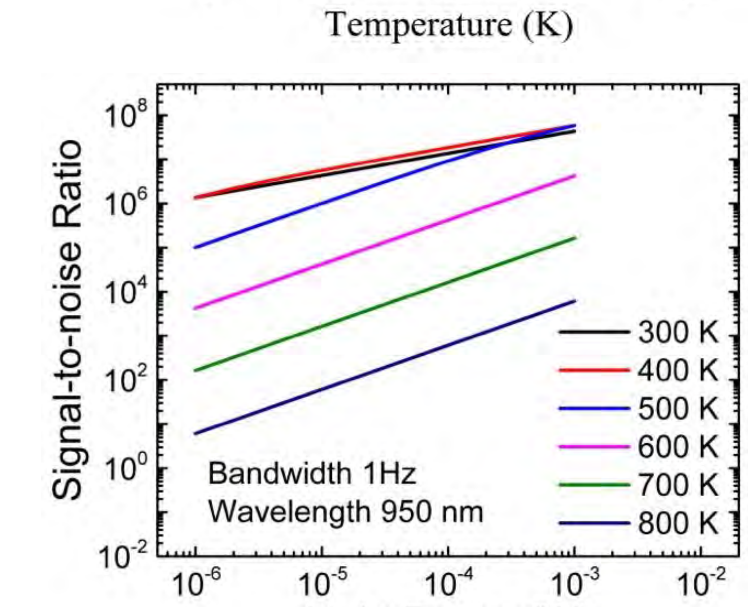
Results

- An unique high temperature optical and electrical characterization setup is finished
- High temperature characterizations on commercial LED materials to analyze the quantum efficiency change from 10K to 800K
- High temperature characterizations on LED and detector devices
- Packaging material and optocoupler high temperature characterization platform









Future Works

- High temperature LED and detector device reliability
- Signal to noise ratio analysis on gate driver with optocoupler in power modules
- Prototype of high temperature packaging with LED and detector devices

Acknowledgment

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Advanced Bi-Additive Vanadium Electrolyte

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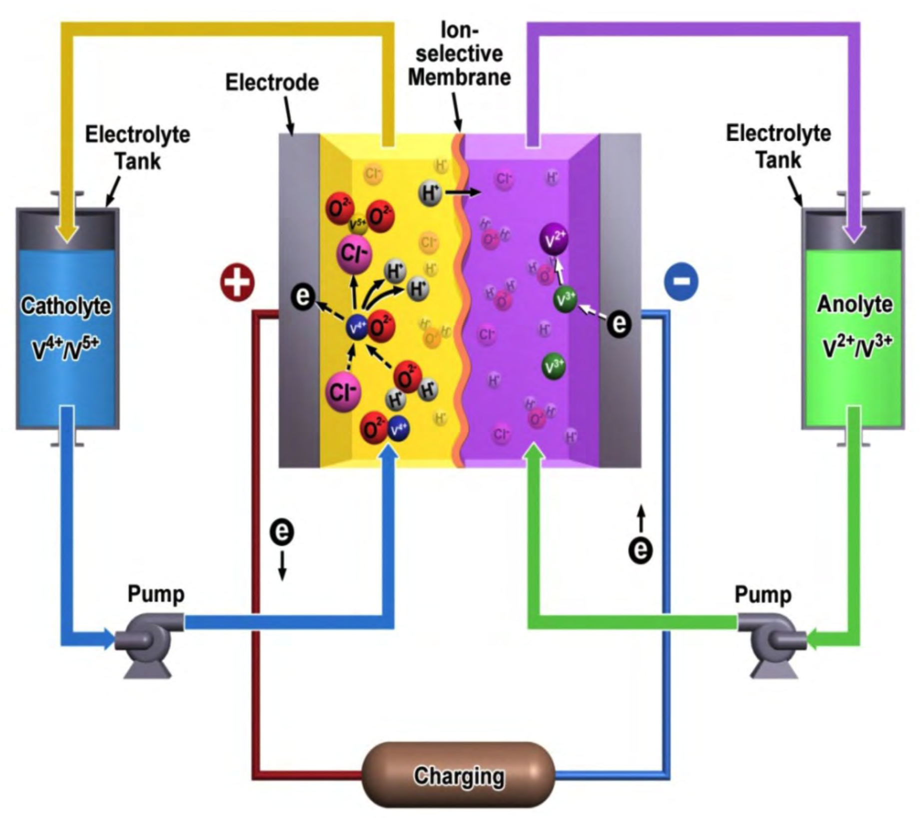
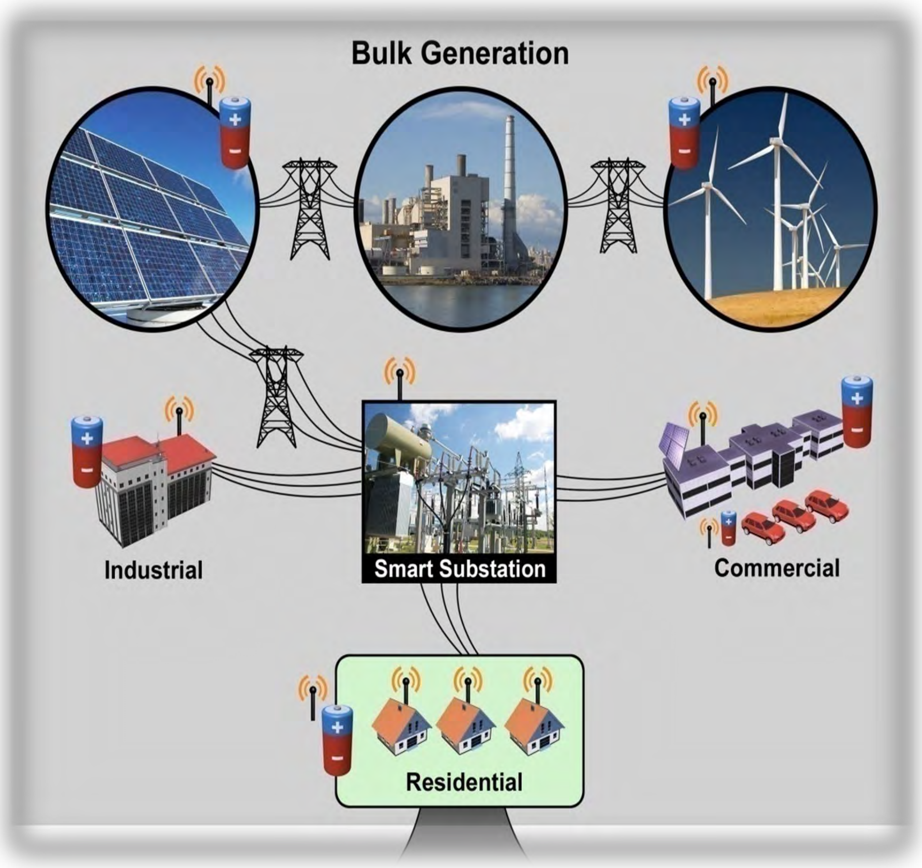
Introduction:

Redox Flow Batteries

A promising energy storage option for the future grid



Advantages
- Large-scale storage
- Decoupled Power/energy
- High safety
- Modular design



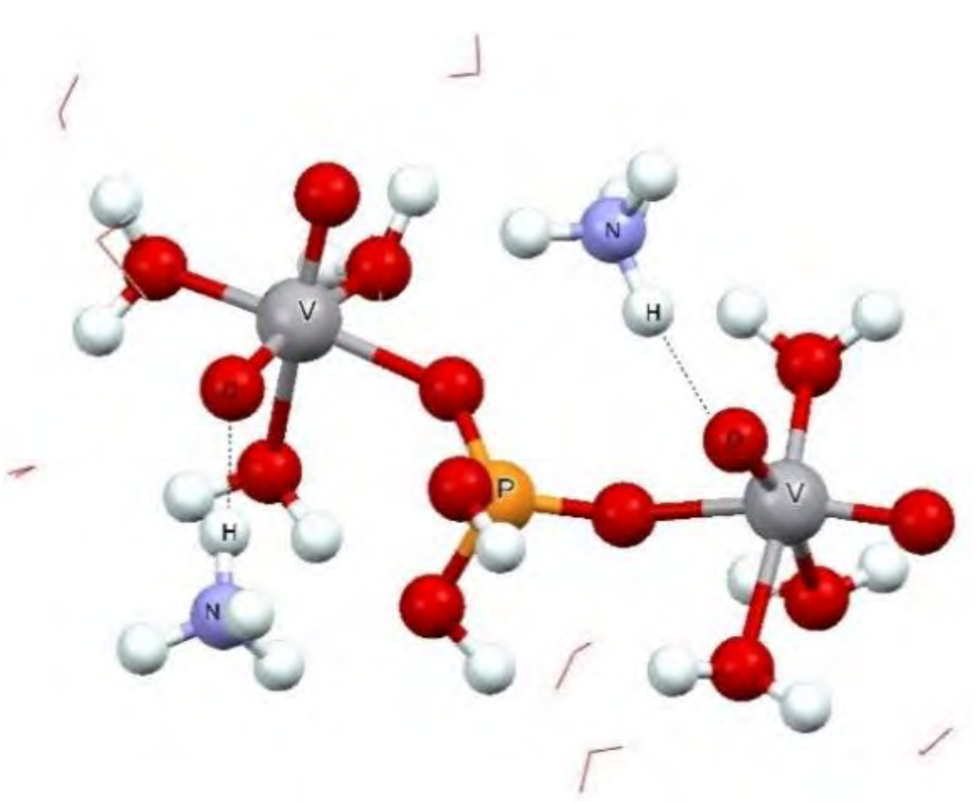
Applications
- Renewable energy integration
- Improve grid reliability
- Enable smart grid deployment

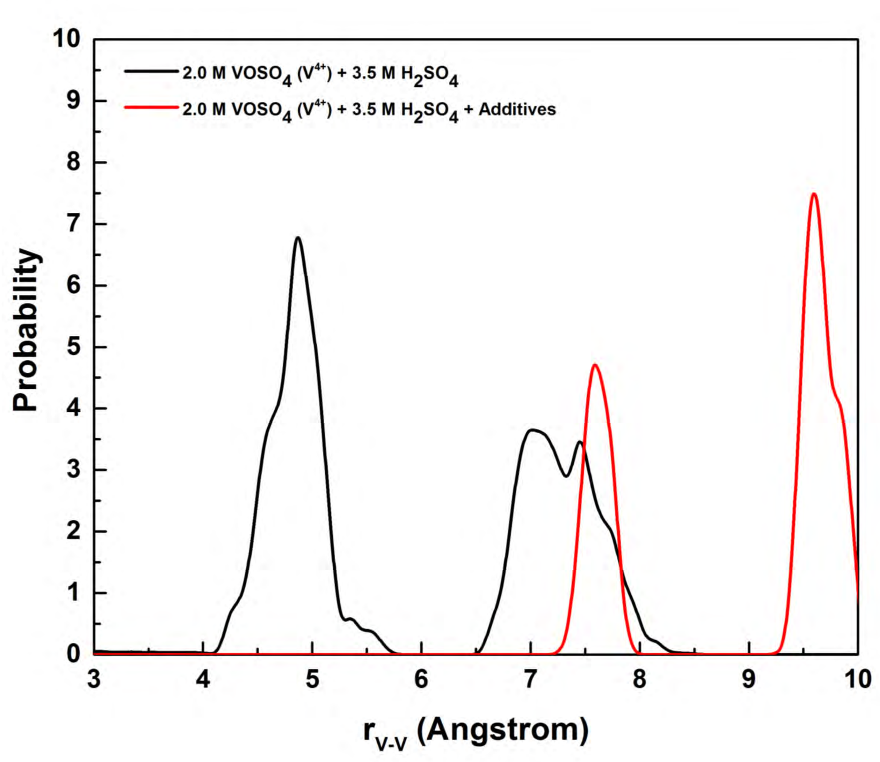
Objectives:

- **Develop V electrolyte with higher concentration**
- **Stabilize V electrolyte in a wider temperature range**

Results and Discussion:

Bi-additive system containing $(NH_4)_2HPO_4$
Increase the intermolecular distance

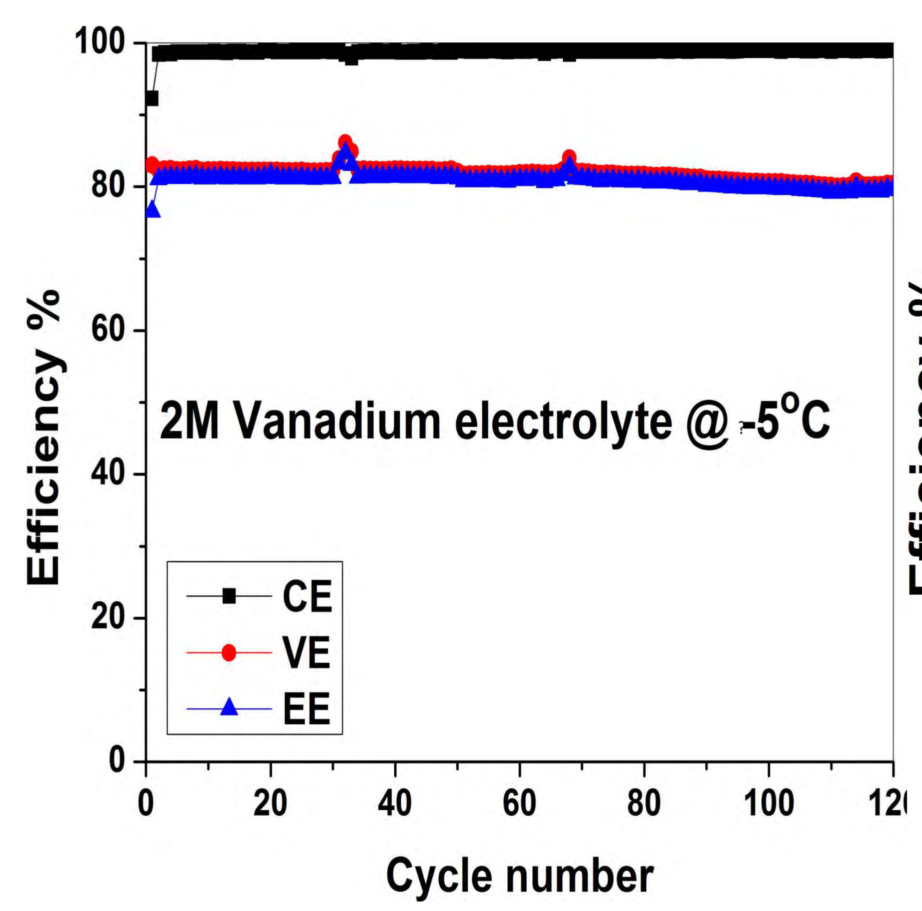


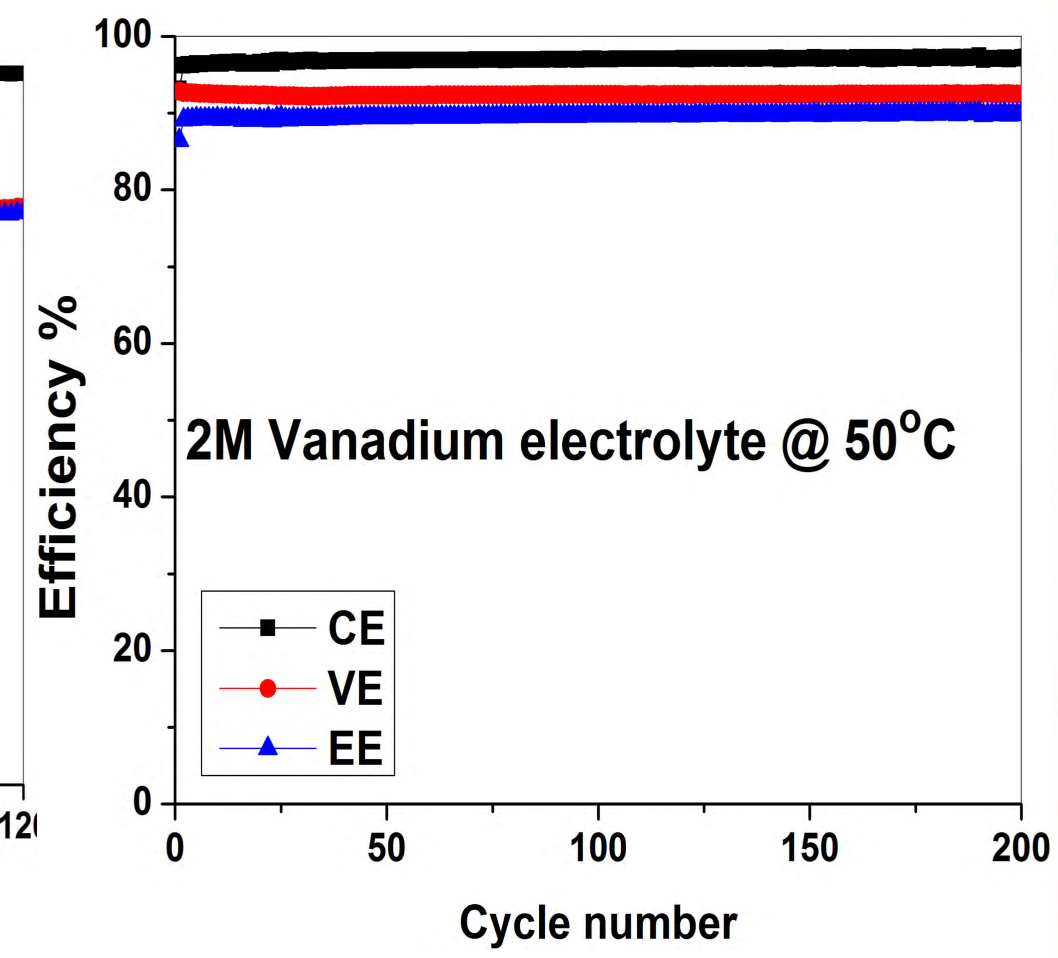


Enhanced Electrolyte Property

V species	-5°C	40°C	-5°C	50°C
	sulfate	sulfate	Sulfate and additives	Sulfate and additives
V^{4+} (VO^{2+})	2M < 1 d	2M >20 d	2M >20 d	2M >20 d
V^{5+} (VO_2^+)	2M < 1 d	2M < 4 d	2M >20 d	2M >20 d

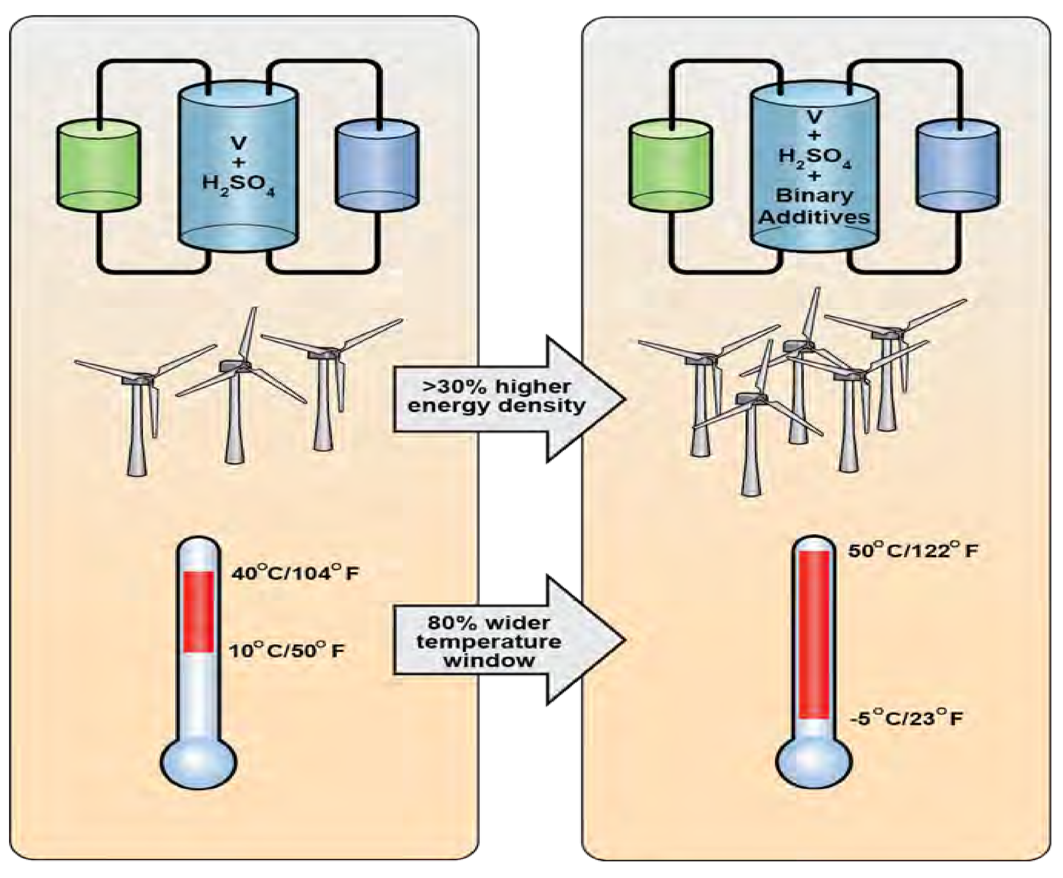
Improved Flow Battery Performance





Summary and Perspective:

30% Higher energy density
80% Wider temperature window



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