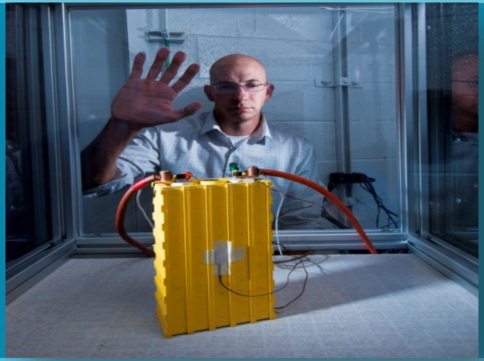
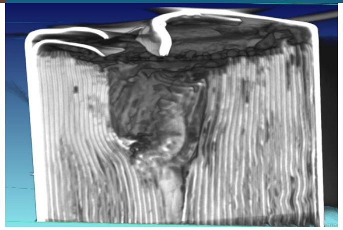
SAND2021-6800PE

Battery Safety and Reliability: Tools to understand risk in grid-scale energy storage systems





DOE 2021 Lunch & Learn Series

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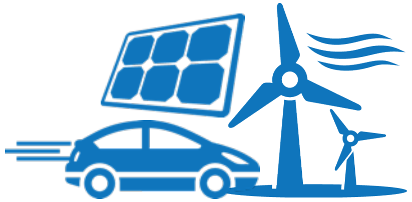
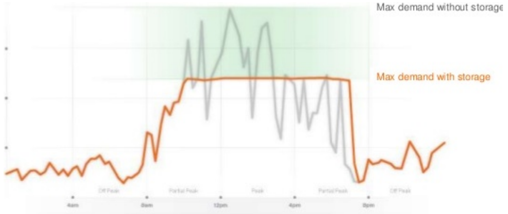
Role of energy storage in the grid

- Renewables integration to address climate change
- Grid resiliency and reliability
- Improving power quality
- Improving the efficiency of existing generation fleet
- Demand management
- Transmission & Distribution upgrade deferral
- Off-grid applications



Balance the variability of 825 GW of new renewable generation while improving grid reliability and efficiency

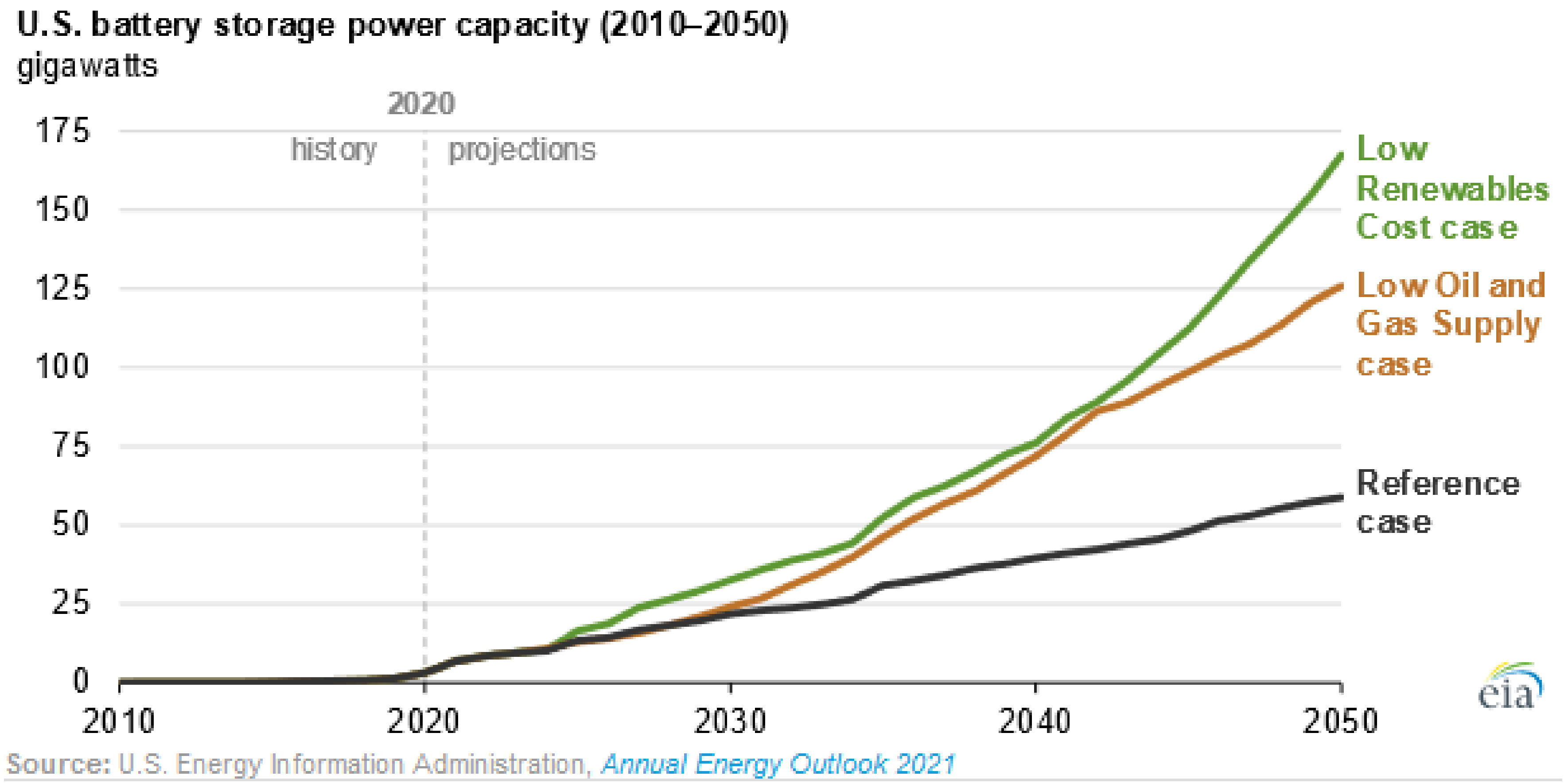
Mitigate $79B/yr in commercial losses from outages



Reduce commercial and industrial electrical bills through demand charge management. 7.5 million U.S. customers are enrolled in dynamic pricing (EIA 2015)

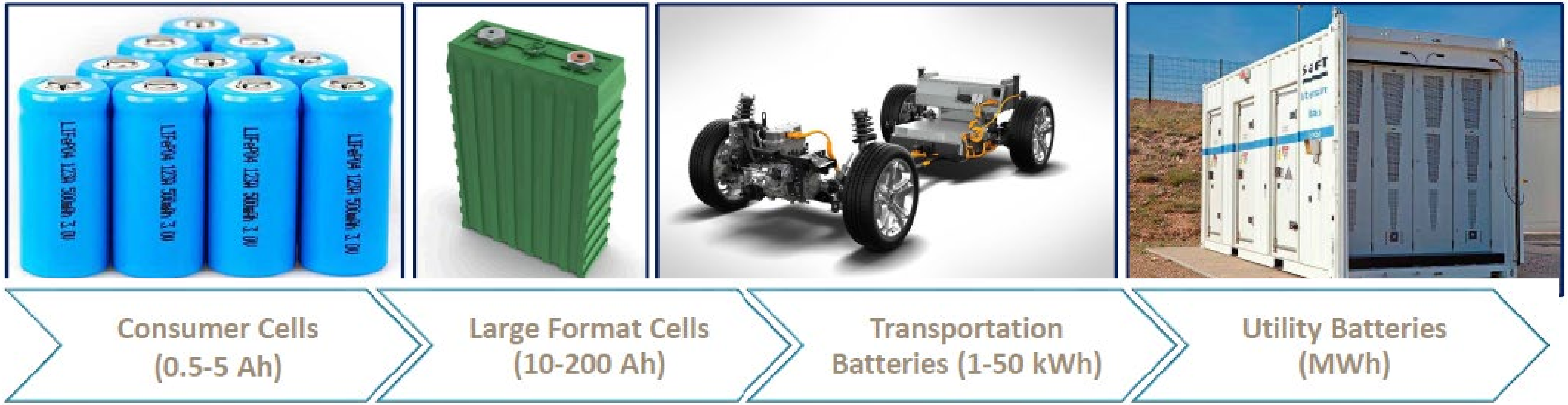
Batteries will provide substantial grid-scale energy storage

Energy Information Administration Annual Energy Outlook 2021 report projects 59 GW of battery energy storage on the grid by 2050 in the base case, 175 GW if more renewables



https://www.eia.gov/todayinenergy/detail.php?id=47276

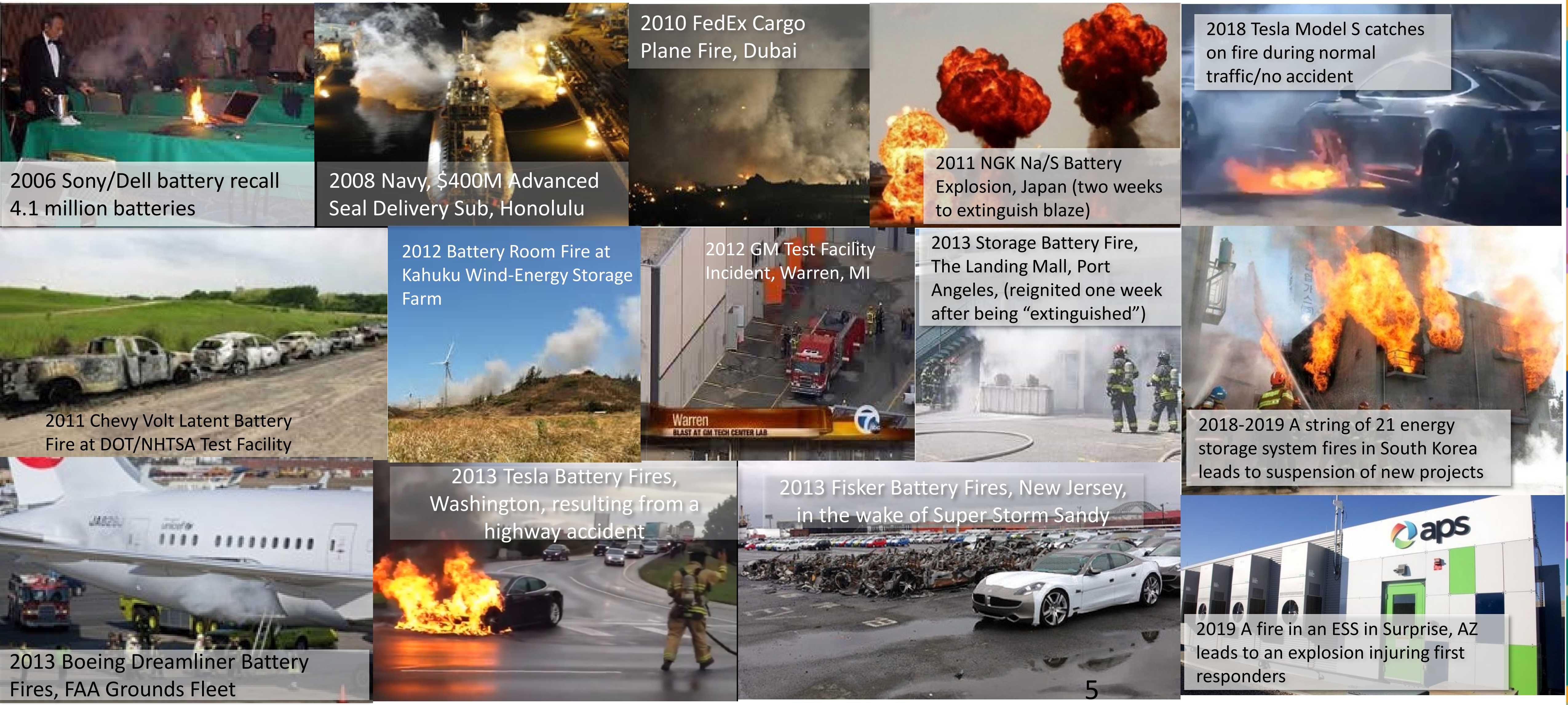
Impact and consequence of scale on safety



Safety issues and complexity increase with battery size

Safety research is heavily focused on lithium-ion as the primary application ready technology. However many emerging technologies identified as promising for grid-scale storage are less well studied.

Grid ESS are the new frontier of battery safety



Safety of ESS is getting increasing media coverage

Bloomberg

Hyperdrive

Explosions Threatening Lithium-Ion's Edge in a Battery Race

By Brian Eckhouse and Mark Chediak
April 23, 2019, 4:58 PM MDT *Updated on April 24, 2019, 8:24 AM MDT*

- Battery exploded at plant in Arizona; two others were shut
- Arizona utility regulator calls for 'thorough investigation'

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Another lithium-ion battery has exploded, this time at an energy-storage complex in the U.S.

At least 21 fires had already occurred at battery projects in South Korea, according to BloombergNEF. But this latest one, erupting on Friday at a facility owned by a Pinnacle West Capital Corp. utility in Surprise, Arizona, marked the first time it has happened in America since batteries took off globally.

Greentech Media

APS and Fluence Investigating Explosion at Arizona Energy Storage Facility

The stakes are high for the energy storage sector after an explosion with an unknown cause left several firefighters injured.

KARL-ERIK STROMSTA | APRIL 22, 2019

15

Earlier this year APS announced plans to build 850 megawatts of battery storage by 2025.

Fluence has dispatched a team of experts to help utility Arizona Public Service determine what caused an explosion at one of its grid-scale battery facilities. The explosion on Friday reportedly left four firefighters injured, including three who were sent to a burn center.

Firefighters responded to a call on April 19 after smoke was seen rising from APS' McMicken Energy Storage facility, one of two identical 2-megawatt/2-megawatt-hour grid-scale batteries the utility installed in 2017 in Phoenix's growing West Valley region.

According to local press reports, the firefighters were inspecting the facility's lithium-ion batteries when they were hit with an explosion. Several of the firefighters received chemical burns, the local fire department told the *Arizona Republic*.

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Frequent fire raising concerns over safety of solar energy

A fire engulfs an energy storage system at a cement plant in Jecheon, North Chungcheong Province, Monday. / Courtesy of North Chungcheong Province Fire Service Headquarters

By Nam Hyun-woo

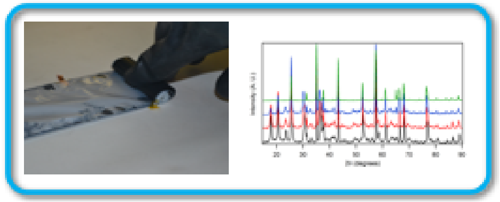
A series of fires in energy storage systems (ESSs) has been raising safety concerns, according to industry analysts, Tuesday.

With ESSs essential for optimizing energy efficiency, further accidents may compromise the feasibility of renewable power and hamper the government's bid to expand the use of cleaner energies.

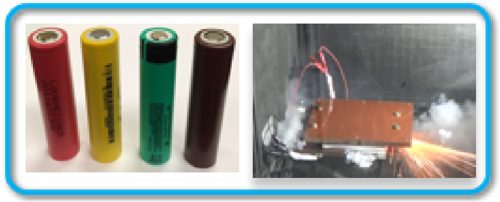
According to the Ministry of Trade, Industry and Energy, it recommended individuals, companies and other organizations to stop using 584 uninspected ESSs across the country.

Safety concerns could serve as a barrier to broader deployment of grid energy storage systems

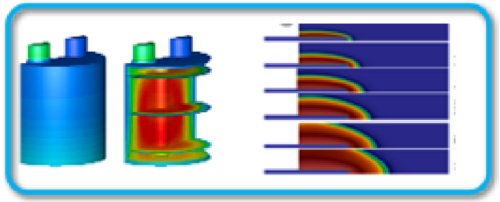
Sandia addresses all aspects of safety & reliability for battery energy storage



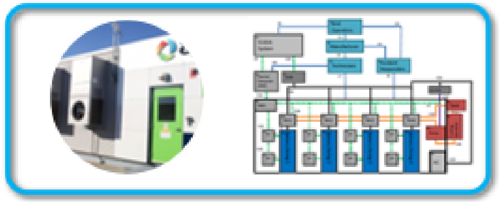
Materials R&D
- Thermal stability and impact of aging on battery components
- Vent gas composition



Cell and Module Testing
- High precision cell cycling and degradation
- Electrical, thermal, mechanical abuse testing
- Failure propagation testing on batteries/systems



Simulations and Modeling
- Multi-scale models for understanding thermal runaway
- Fire Dynamic Simulations to predict the size, scope, and consequences of battery fires



System Level Design and Analysis
- Hazard analysis methods to avoid fire and explosion
- Predictive maintenance

UL IEEE IEC ASME EPRI

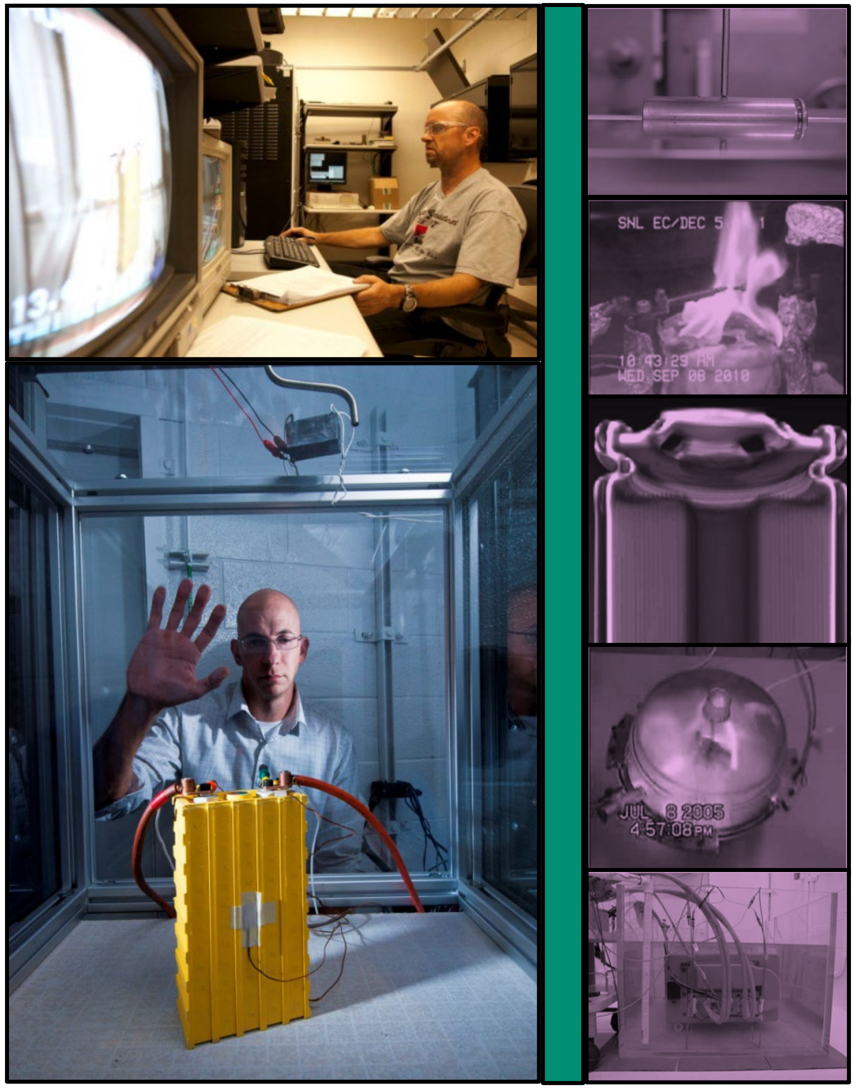
Outreach, Codes, and Standards
- Energy storage safety working group
- IEEE battery management system standard

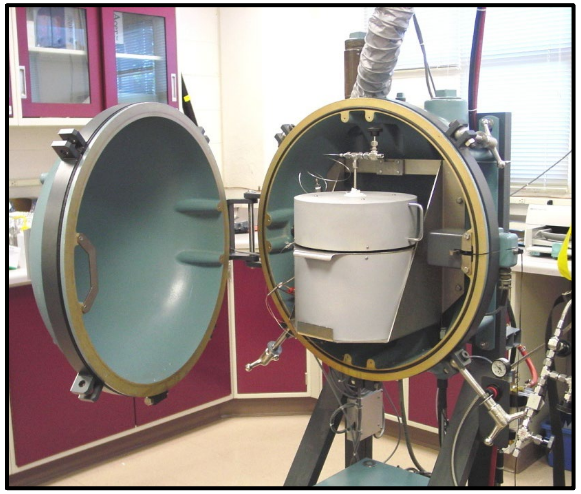
Dedicated facilities for battery testing

- Hundreds of independent channels for testing, from coin cells to kWh modules
- 150 uA to 2000 A current range capability
- R&D 100 Green Technology-awarded high-precision testers
- 70+ thermal chambers, ranging from 1.2 ft^3 to 25 ft^3
- –72°C to 95°C temperature capabilities
- Welding capabilities, including resistance, pinch, and spot
- Additional labs for materials characterization and 8000 ft^2 dry-room space for prototyping

World-class battery abuse lab (DOE Core facility)

- Comprehensive abuse testing platforms for safety and reliability of cells, batteries and systems from mWh to kWh
- Mechanical abuse
  - Penetration
  - Crush
  - Impact
  - Immersion
- Thermal abuse
  - Over temperature
  - Flammability measurements
  - Thermal propagation
  - Calorimetry
- Electrical abuse
  - Overvoltage/overcharge
  - Short circuit
  - Overdischarge/voltage reversal
- Characterization/Analytical Tools
  - X-ray computed tomography
  - Gas analysis
  - Surface characterization
  - Optical/electron microscopy





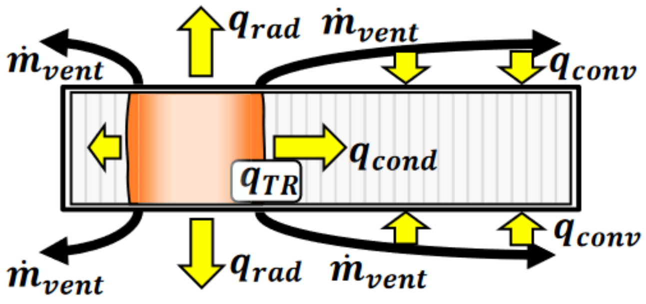
Approaches to designing in safety

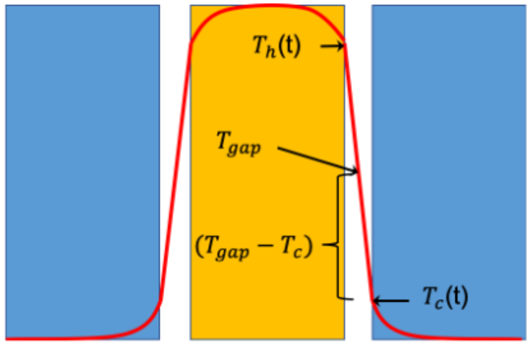
The current approach is to test our way into safety.

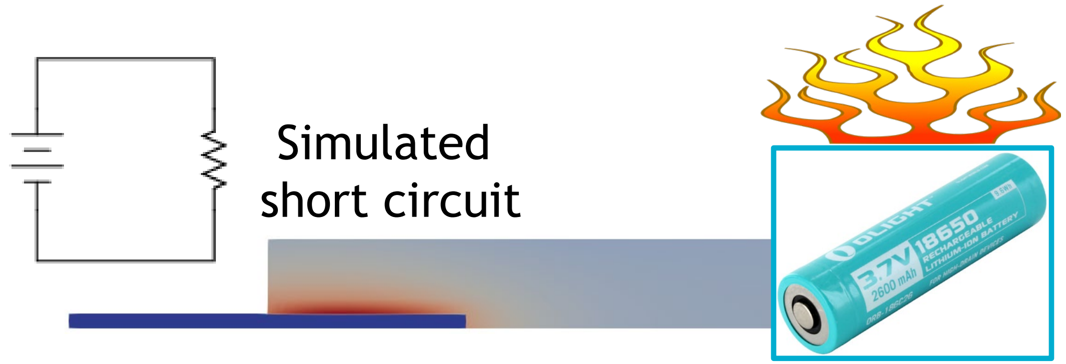
- Large system (>1MWh) testing is difficult and costly

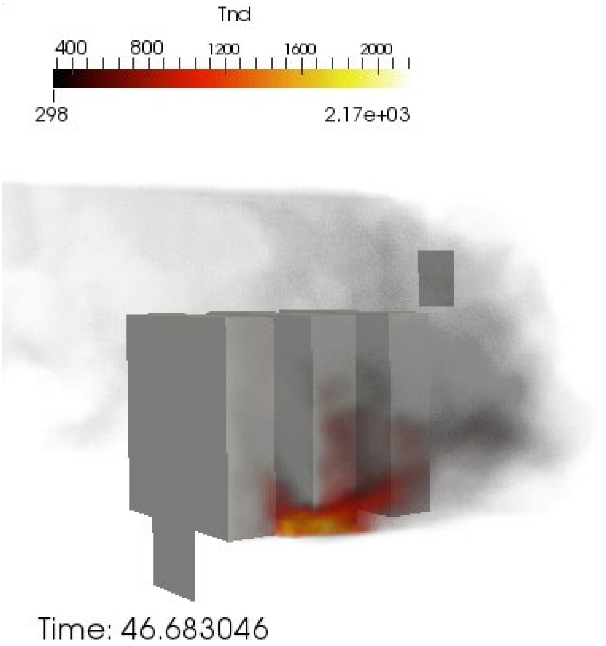
Supplement testing with predictions of challenging scenarios and optimization of mitigation

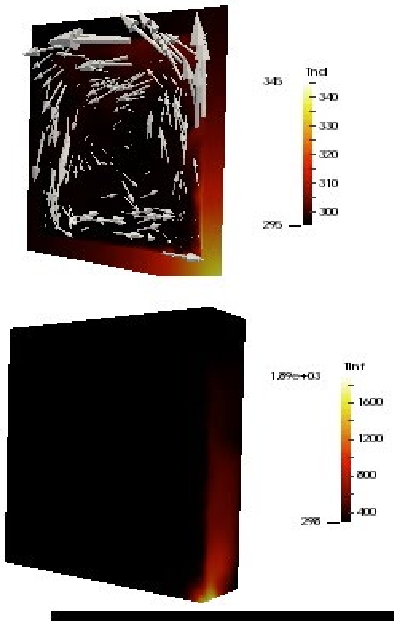
- Leverage world-class fire sciences, thermal modeling, and computing resources at SNL
- Develop multi-physics models to predict failure mechanisms and identify mitigation
- Build capabilities with small/medium scale measurements
- Still requires some testing and validation





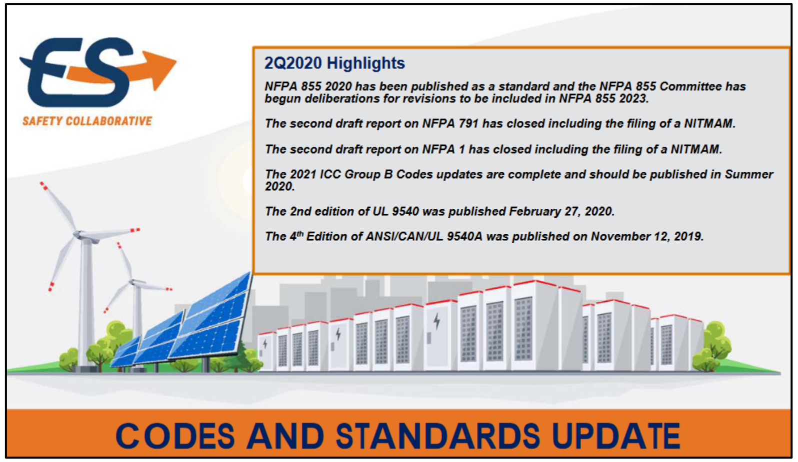


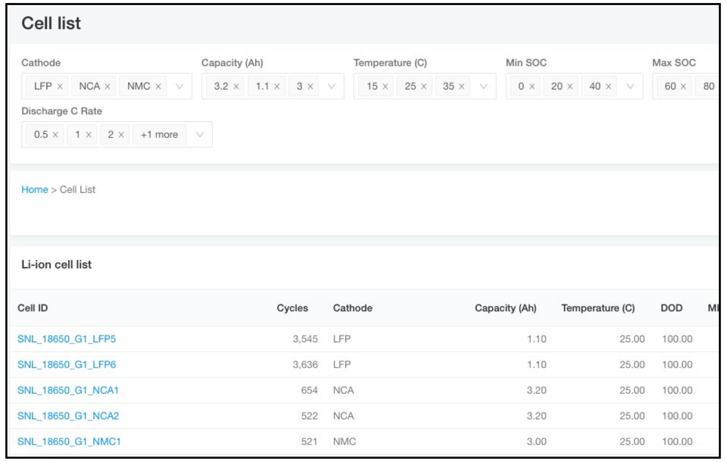




Advancing energy storage systems

1. Supporting incident investigation
2. Developing informational reports and guides with energy storage safety stakeholders
3. Sharing open source software and data

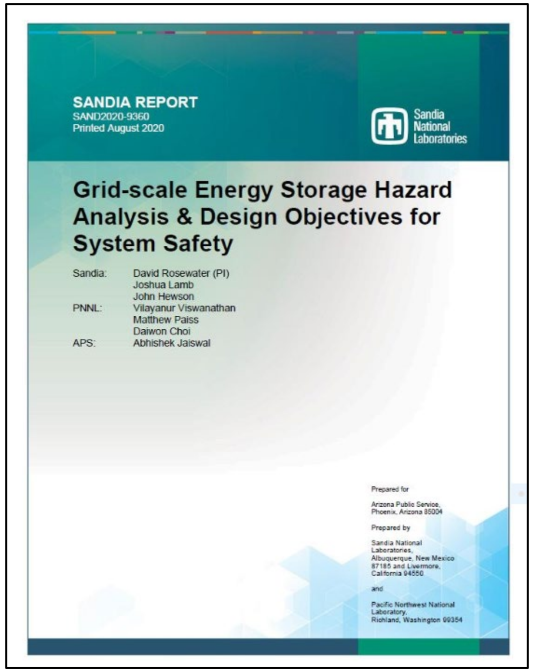




Cell ID	Cycles	Cathode	Capacity (Ah)	Temperature (C)	DOD
SNL_18650_G1_LFP5	3,545	LFP	1.10	25.00	100.00
SNL_18650_G1_LFP6	3,636	LFP	1.10	25.00	100.00
SNL_18650_G1_NCA1	654	NCA	3.20	25.00	100.00
SNL_18650_G1_NCA2	522	NCA	3.20	25.00	100.00
SNL_18650_G1_NMC1	521	NMC	3.00	25.00	100.00

Supporting grid energy storage incident investigation

- 2019 battery energy storage system (BESS) fire in Surprise, Arizona – first instance of injury to first responders
- Safety team members provided neutral subject matter expertise to utility and first responders
- Published follow-up report on “Grid-scale Energy Storage Hazard Analysis and Design Objectives for System Safety”


SANDIA REPORT
SAND2020-9360
Printed August 2020

Sandia National Laboratories

Grid-scale Energy Storage Hazard Analysis & Design Objectives for System Safety

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and

Pacific Northwest National Laboratory,
Richland, Washington 99354

Source: David Rosewater, Joshua Lamb, John Hewson

Leading outreach in energy storage safety

- Energy Storage Safety Collaborative formed in 2014 in response to a series of grid-scale battery fires
- Energy Storage Safety Strategic Plan published (currently undergoing revision)
- Annual Energy Storage Safety and Reliability Forum brings ~150 stakeholders annually to review the latest concerns and research
- Quarterly reports on the status of safety related codes and standards
- Engagement with NFPA, IEEE, and UL on education and standards development

Safety Collaborative Site: https://www.sandia.gov/energystoragesafety-ssl/

Source: Joshua Lamb, David Rosewater

Collaborating with EPRI on energy storage data and alarm management guide

- Review of energy storage data received from providers has shown that they're inconsistent and incomplete
- Robust data is key to safety & reliability analysis, including evaluation of performance claims
- 2020 EPRI-SNL V1 Guide proposed general guidelines for sampling rates and data points
- 2021 V2 Guide adds an alarm management framework and discussion of data quality/accuracy

Data Point	Units	Sample Rate Minimum	Power Application Report Out Minimum	Energy Application Report Out Minimum	Values
Flicker	Pst	≥500 Samples/Second	≥1 Sample/Second	≥ 1 Sample/15 minutes	value, max, min, avg
System Frequency	Hz	≥1 Sample/Second	≥1 Sample/Second	≥ 1 Sample/15 minutes	value, max, min, avg
THD	dBm	≥500 Samples/Cycle	≥1 Sample/Second	≥ 1 Sample/15 minutes	value, max, min, avg
DC Power	kW	≥1 Sample/Second	≥1 Sample/Second	≥ 1 Sample/15 minutes	value, max, min, avg
DC Voltage	V	≥1 Sample/Second	≥1 Sample/Second	≥ 1 Sample/15 minutes	value, max, min, avg
DC Current	I	≥1 Sample/Second	≥1 Sample/Second	≥ 1 Sample/15 minutes	value, max, min, avg
State of Charge	%	≥1 Sample/Second[4]	≥1 Sample/Second	≥ 1 Sample/15 minutes	value, max, min, avg
State of Health	%	≥1 Sample/Second	≥1 Sample/Second	≥ 1 Sample/15 minutes	value, max, min, avg
Total DC Discharge Energy	kWh	≥1 Sample/Second	≥1 Sample/Second	≥ 1 Sample/15 minutes	value, max, min, avg

EPRI-SNL V1 Guide: https://www.osti.gov/servlets/purl/1602954

Source: David Rosewater, Yuliya Preger

Sharing battery safety tools with the community

Launched heat release calculator based on Li-ion battery materials composition

Composition Case Formula(s)

Name of Layered Metal Oxide	Cathode Mass	Ni Content*	Co Content*	Mn Content*	Al Content*	Total	x = DoL	LMO Formula
Metal Composition 1	Optional	0.00	0.00	0.00	0.00	0.00	0.00	Li_xMO_2

*Required field

Oxidation Enthalpy (kJ/mol O_2, for electrolyte solvent, etc.): -460.5

Ni cut-off for M_3O_4 formation: 0.50

Calculate

Lithium-ion Battery Thermodynamic Web Calculator

Results for:

Oxidation Enthalpy: -460.5 kJ/mol O_2

Ni Cutoff: 0.5

Case 1: Name = "NMC", Composition = $Li_{0.5}Ni_{0.333}Co_{0.333}Mn_{0.333}O_2$ (x = 0.5, M = $Ni_{0.333}Co_{0.333}Mn_{0.333}$)

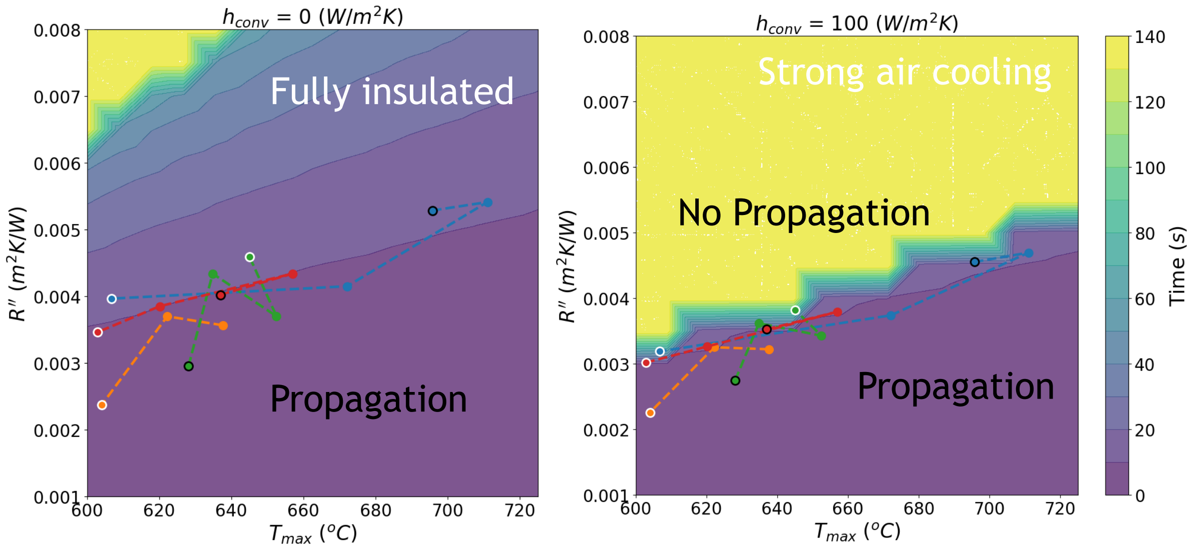
Summarized Output:

Heat Release Summary with Solvent Oxidation and Increments [ΔH_r (J/g Li_xMO_2)] (Assumes Low Nickel Content)

	$MO_2 \rightarrow LiM_2O_4$ Initial Reaction 4 Low Temp Increment	$MO_2 \rightarrow M_3O_4$ Reaction 2 Med Temp Increment	$MO_2 \rightarrow LiM_2O_4 + M_3O_4$ Reaction 9 Med Temp Cumulative	$LiM_2O_4 + M_3O_4 \rightarrow MO$ Reaction 11 High Temp Increment	$MO_2 \rightarrow MO$ Global Reaction 1 Cumulative Total Heat Release
Case 1:	-225.8	0.0	-225.8	-691.7	-917.5

Source: Randy Shurtz
https://www.sandia.gov/ess-ssl/thermodynamic-web-calculator/

Developing simulator of module-level thermal runaway propagation



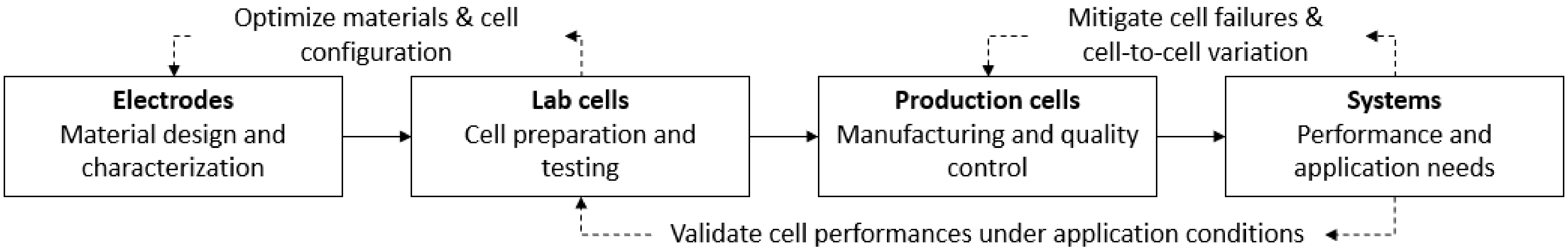
Source: Andrew Kurzawski

Developed Battery Lifecycle Framework for battery data analysis

- Battery Lifecycle Framework (BLC) is an open-source platform that provides tools to visualize, analyze, and share battery data through the technology development cycle
  - Development began in 2019 with City College of New York

- Linking data across steps key to accelerating development of safe and reliable batteries

- BLC permits linking of multiple data sources, queries, and dashboards to track data from materials to systems

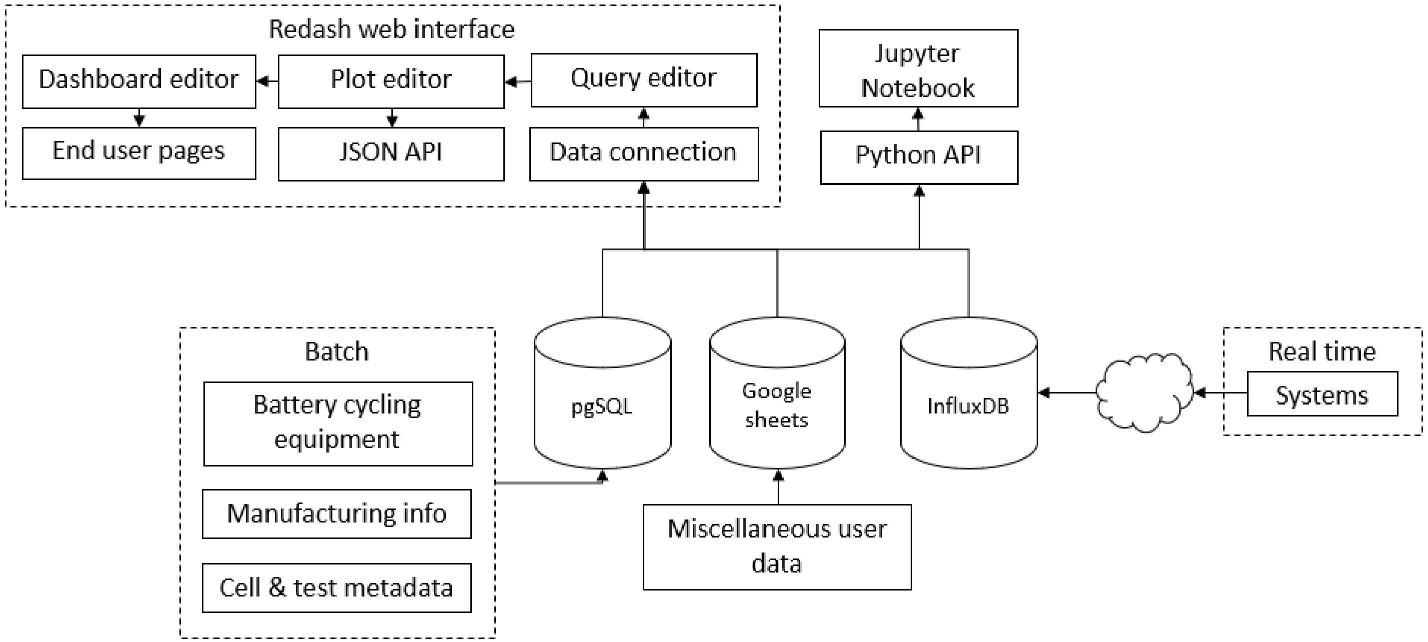


Source: Valerio De Angelis, Yuliya Preger

Open-source platform underpinning the Battery Lifecycle Framework

- BLC has four components: (1) data importers, (2) one or more databases, (3) a front-end for querying the data and creating visualizations, (4) an application programming interface to process the data

- Example implementations:
  - Used by a battery company to track data from the lab to the field
  - Online repository of cell testing data at www.BatteryArchive.org



Preprint: https://ecsarxiv.org/h7c24; Github: https://github.com/battery-lcf/battery-archive-sandbox

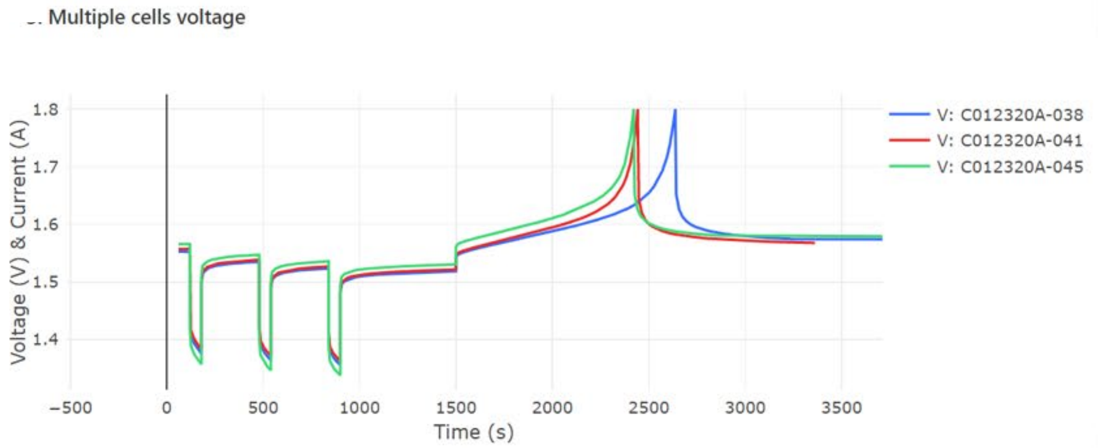
Implementation A: Linking data across a battery's lifetime

Example dashboard used by battery company to track data from lab cells to fielded systems

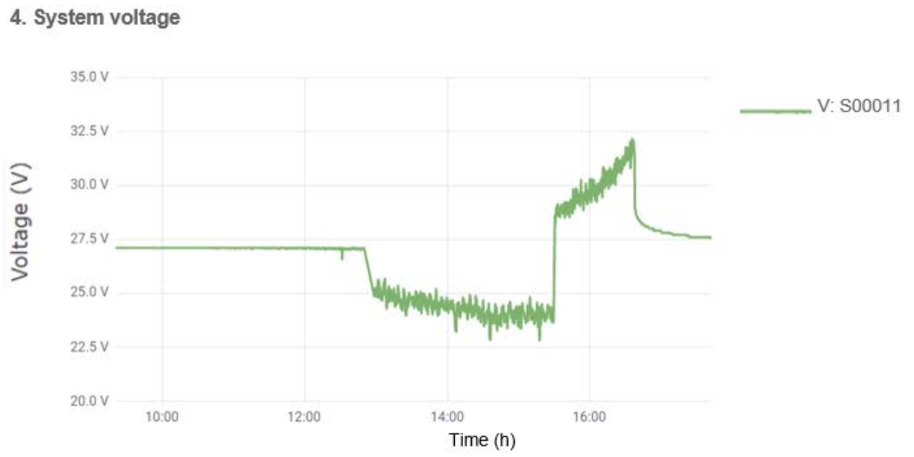
1) Manufacturing data for 3 cells imported into pgSQL database from a FileMaker database

cell_id	study	Anode Batch ID	Cathode Batch ID	Anode Weight (kg)	Cathode Weight (kg)
C012320A-038	3-pulse+1-cycle-Battery 1-SBT	A - 011520	C - 110819	0.98	1.80
C012320A-041	3-pulse+1-cycle-Battery 1-SBT	A - 011520	C - 110819	0.98	1.80
C012320A-045	3-pulse+1-cycle-Battery 1-SBT	A - 012120	C - 110819	0.96	1.86

2) Cell-level pulse testing data imported from Arbin testers (MS Access) and a PEC tester (Oracle Database)



3) InfluxDB data from a fielded system

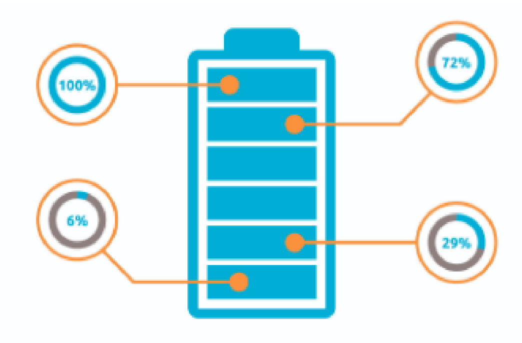


Implementation B: BatteryArchive.org public site

BatteryArchive.org

A repository for easy visualization, analysis, and comparison of battery data across institutions

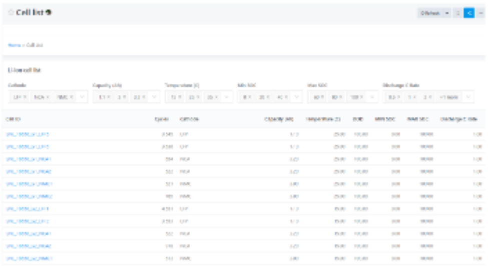
View Data



Features

1

Filter battery data



Query and filter for specific experimental conditions.

2

Visualize and compare data

Display battery data, including voltage curves and capacity fade.

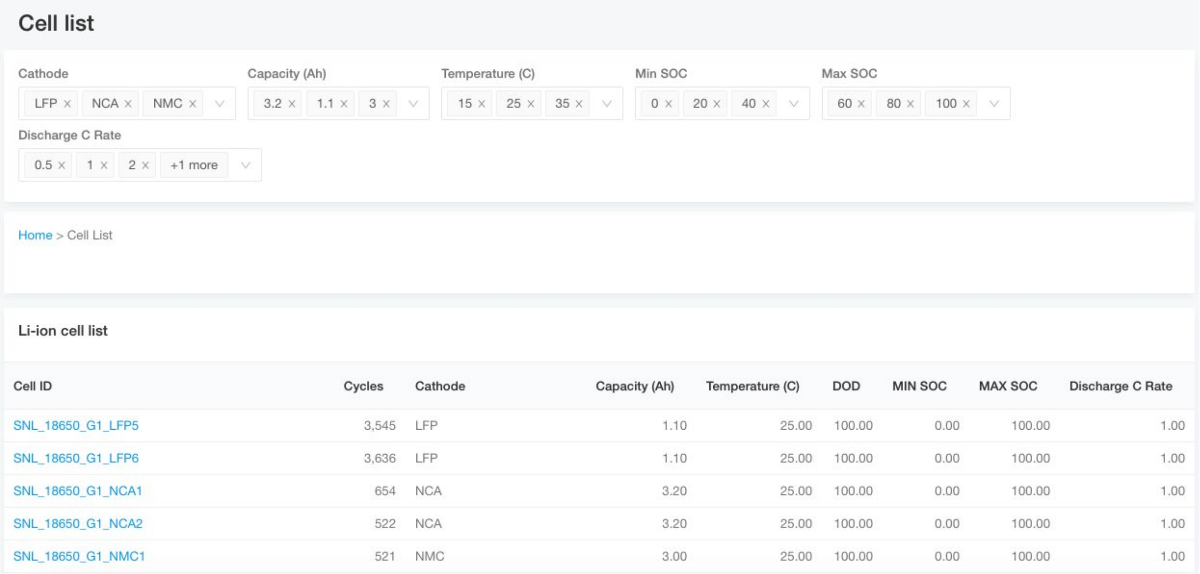
3

Compare data with models

Apply performance and degradation models to battery data.

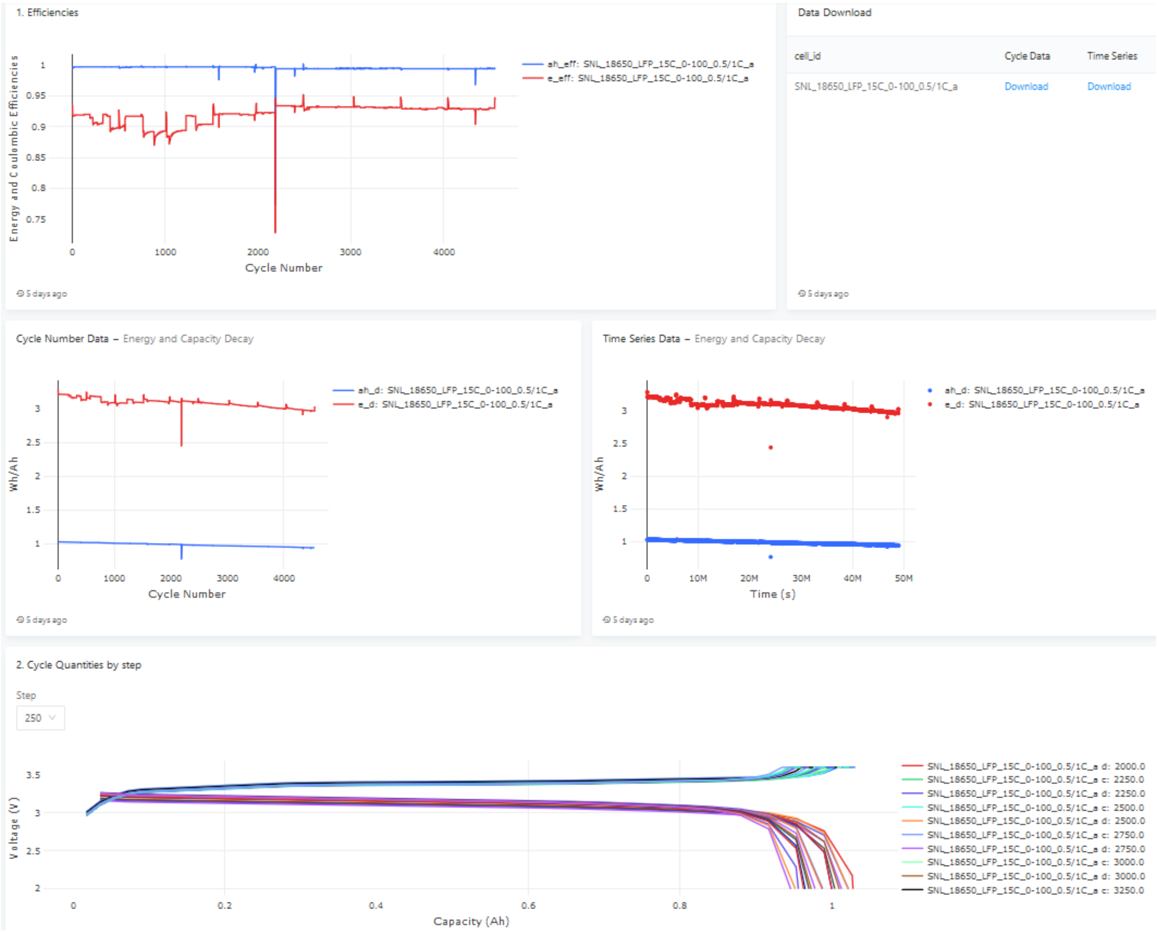
Developing BatteryArchive.org - first multi-institution battery cycling database

Search by metadata related to cell + cycling conditions



Cell ID	Cycles	Cathode	Capacity (Ah)	Temperature (C)	DOD	MIN SOC	MAX SOC	Discharge C Rate
SNL_18650_G1_LFP5	3,545	LFP	1.10	25.00	100.00	0.00	100.00	1.00
SNL_18650_G1_LFP6	3,636	LFP	1.10	25.00	100.00	0.00	100.00	1.00
SNL_18650_G1_NCA1	654	NCA	3.20	25.00	100.00	0.00	100.00	1.00
SNL_18650_G1_NCA2	522	NCA	3.20	25.00	100.00	0.00	100.00	1.00
SNL_18650_G1_NMC1	521	NMC	3.00	25.00	100.00	0.00	100.00	1.00

Efficiencies, capacity and energy decay, and voltage curves automatically plotted for selected cells



All data translated to same format to enable easy comparison

Current status of BatteryArchive.org

Nearly 3000 site users, many return visits, from over 40 countries, academia and industry

Sources of datasets & collaborators

- Datasets online
- Datasets in pipeline
- Software interoperability

Future Directions

- Exploring the safety and degradation risks of advanced technologies
  - *Next generation lithium-ion batteries*: Silicon anode + High nickel cathode materials
  - *Advanced high energy batteries*: Solid state batteries
  - *Advanced chemistries for stationary storage*: Advanced alkaline + flow batteries

- Expanding safety testing and thermal modeling capabilities to accommodate rack- and system-level experiments

- Continuing to provide system-level hazard analysis and maintenance guidance

- Adding open-source modules for data analysis and complete examples of cells to systems datasets to the public BLC Framework

- Controlling battery degradation and thermal runaway using power electronics

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David Rosewater, Chris Searles — Codes & Systems

John Hewson, Andrew Kurzawski, Randy Shurtz — Thermal modeling

Jacob Mueller — Power electronics

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Valerio De Angelis (SNL)

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Front end: Sam Roberts-Baca (SNL)

Database: Mark Spoonamore (SNL)

Early site feedback: Matthieu Dubarry (HNEI)

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Hsin Wang, Michael Starke (ORNL)

Abhishek Jaiswal (Arizona Public Service Electric)

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