SAND2023-04378C

Open-source Software and Open Data to Accelerate the Development of Energy Storage Systems

PRESENTED BY

Valerio De Angelis, Yuliya Preger

Electrochemical Society Meeting

Boston May 30th, 2023

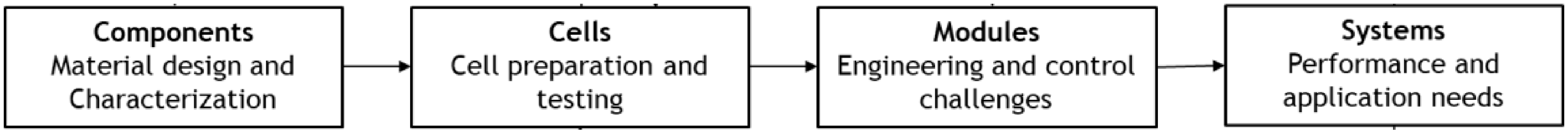
CORE PROJECT MEMBERS

PE: Oindrilla Dutta, Jake Mueller, Andrew Dow

ES: Yuliya Preger, Robert Wauneka, Joseph Lubars

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & 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.

Battery development takes time



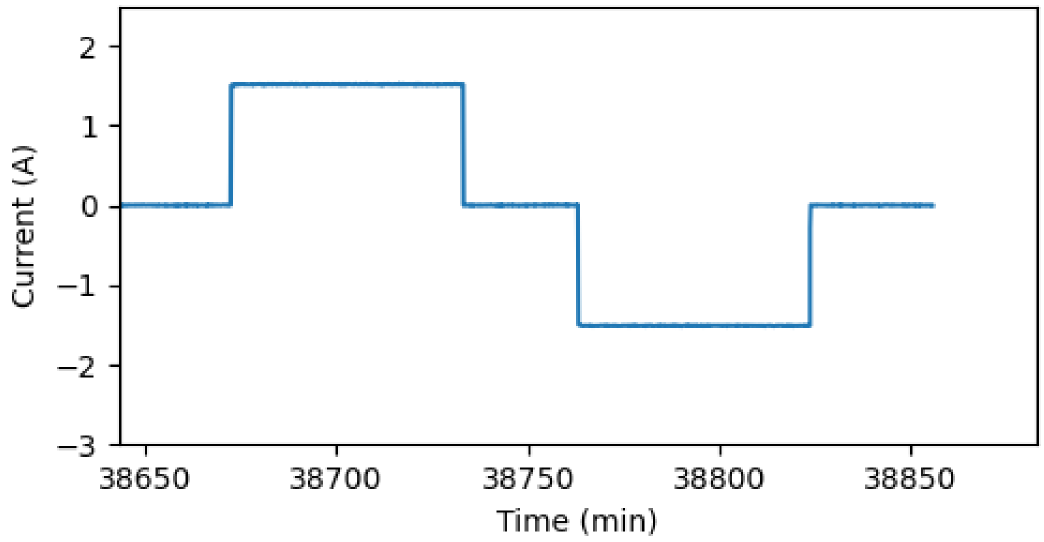
New phenomena are introduced as cells are scaled up

Example 1: Current redistribution among parallel cells

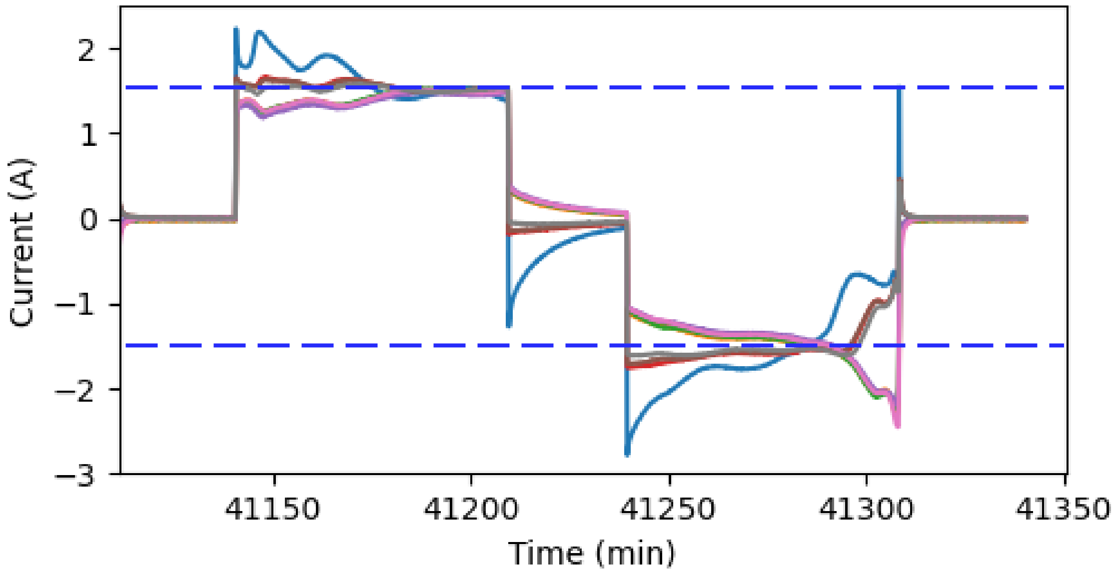
Ideal

Scale-up

Single cell (0.5C/0.5C cycling is 1.5A per cell)



8P-1S module (0.5C/0.5C cycling is 12A per module)

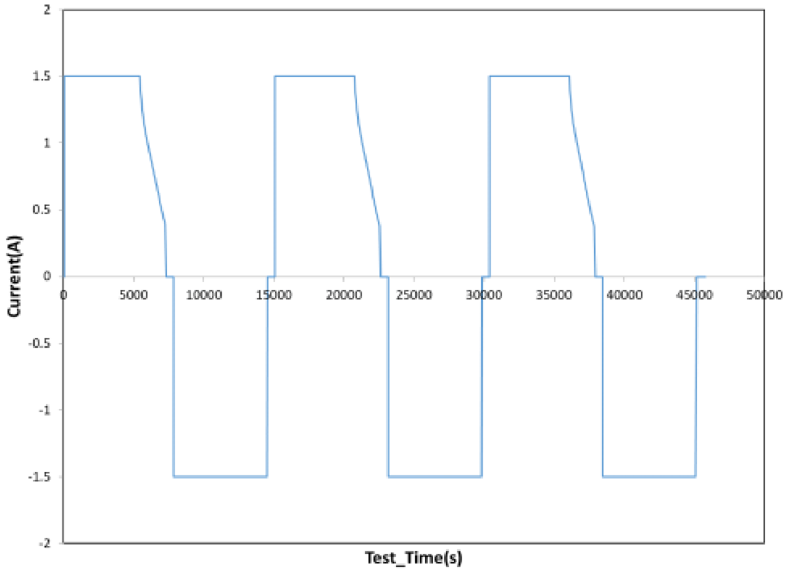


New phenomena are introduced as cells are scaled up

Example 2: Current ripple from power electronics

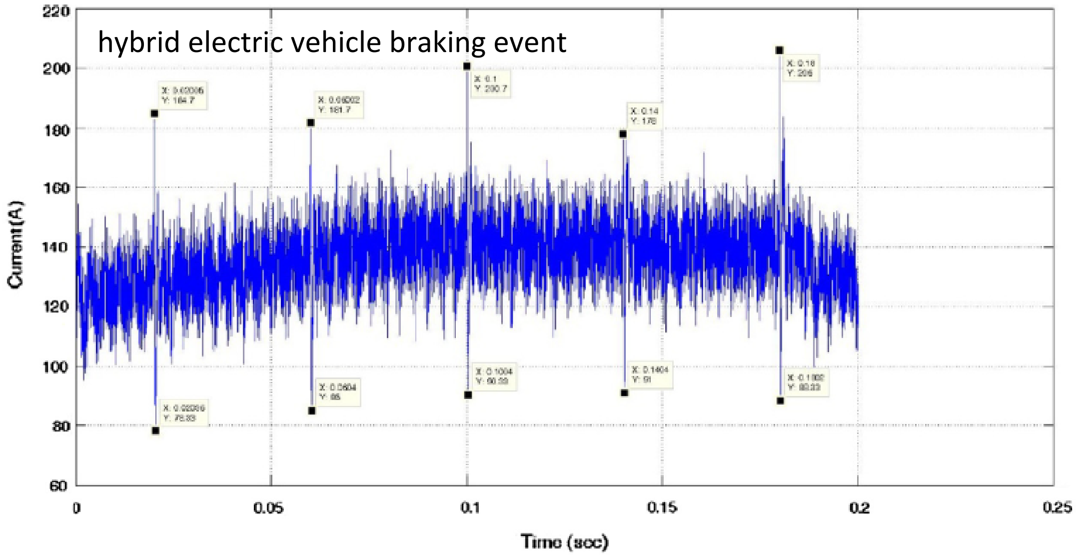
Ideal

Battery tester



Scale-up

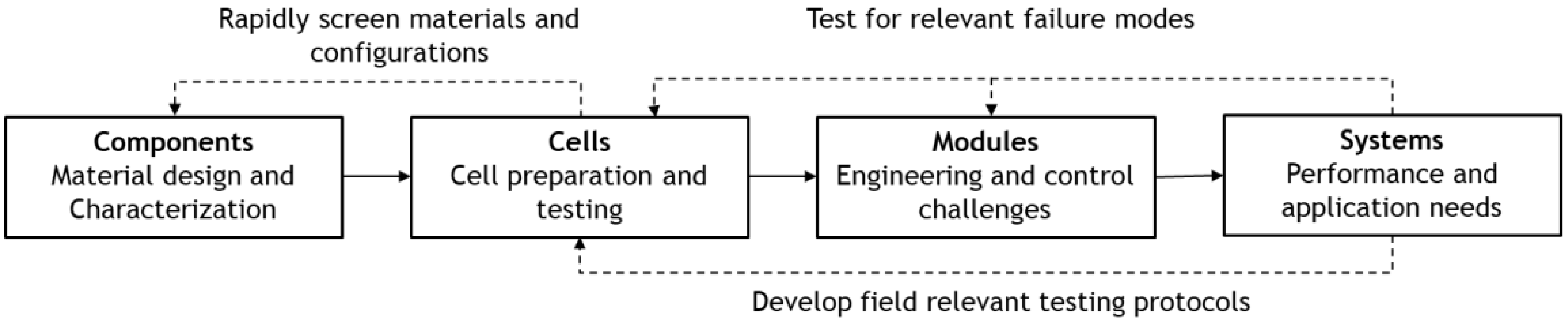
EV or BESS



Uddin et al. *Appl. Energy*, **2016**, *178*, 142.

Lab cycling produces clean DC, but fielded systems have AC ripple from semiconductor switching and AC load dynamics

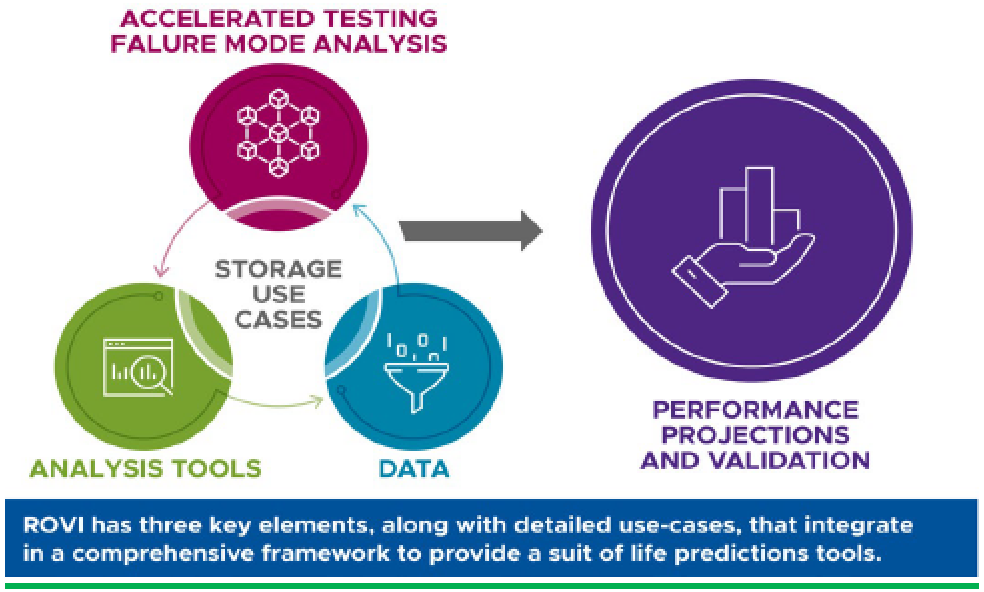
Software and data could help uncover and address problems early on



We need (1) software to aggregate data from different stages of development and (2) standards for data logging

Standardized energy storage data collection now key to DOE efforts

Energy Storage Grand Challenge Rapid Operational Validation Initiative (ROVI) goal is to use data-driven insights to develop accelerated testing and validation methods for new technologies that will yield 15+ years of performance projections with less than one year of data



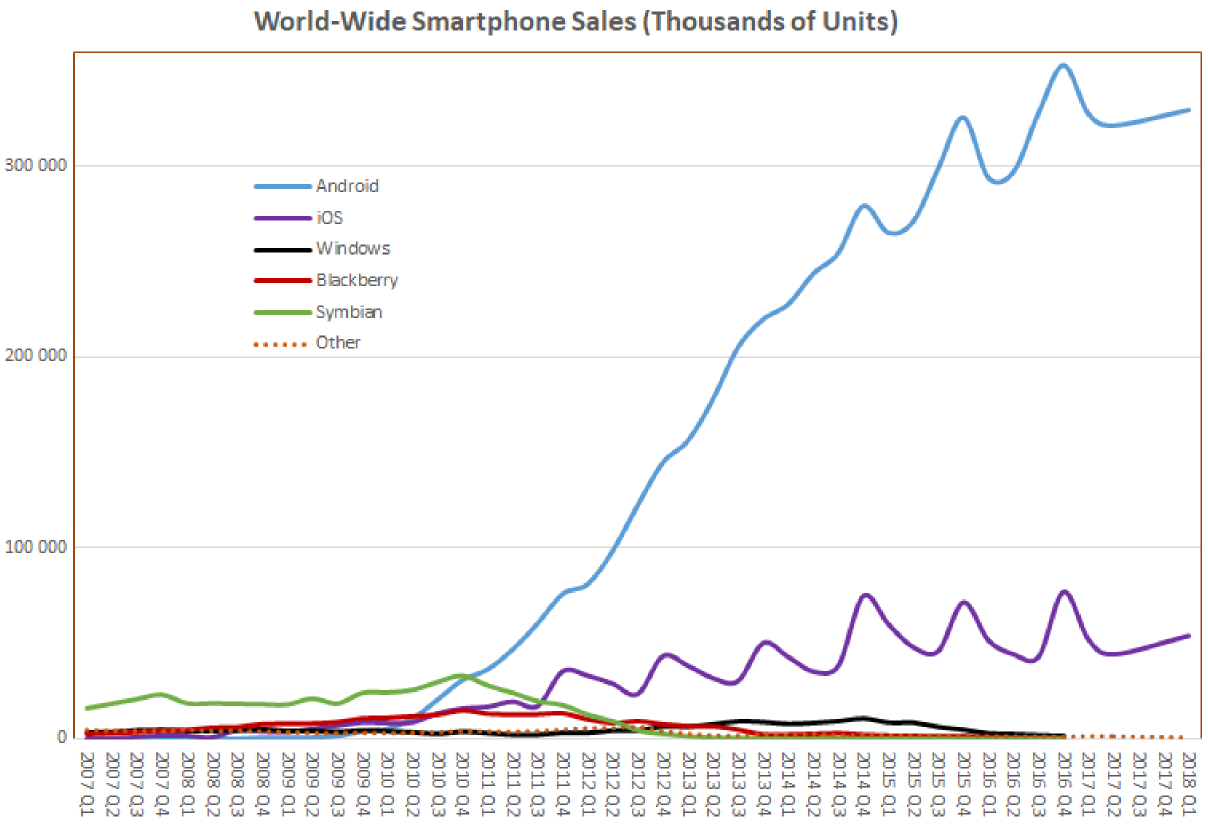
ROVI will inform data collection requirements for >$500 million of DOE-funded demonstration projects.
Sandia is leading the development of the data infrastructure (software and reporting requirements).

No commercial package includes all the tools needed by the battery industry

Open-source software can help: Innovation, Freedom, Integrity, Continuity, Sharing

There are over 2M open source projects on Github, and many contain the building blocks that we need

Open-source software powers smartphones around the world, supercomputing centers, and web servers



Not even Apple can compete with open-source software!

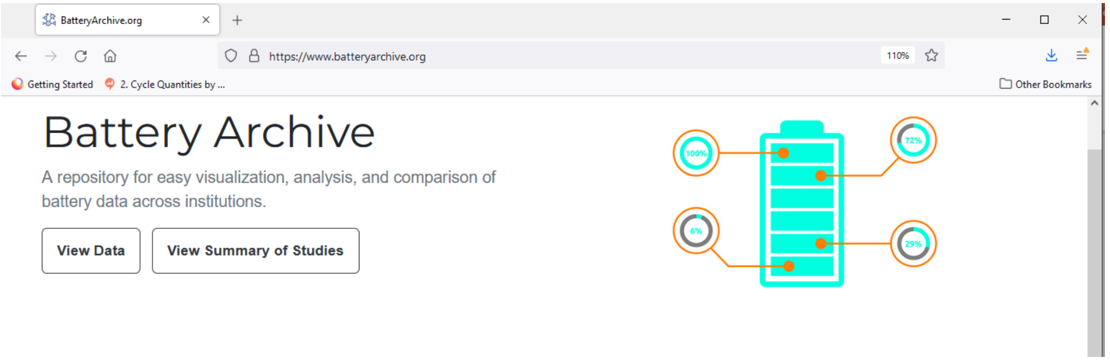
We are building an ***open*** energy storage system from the ground up

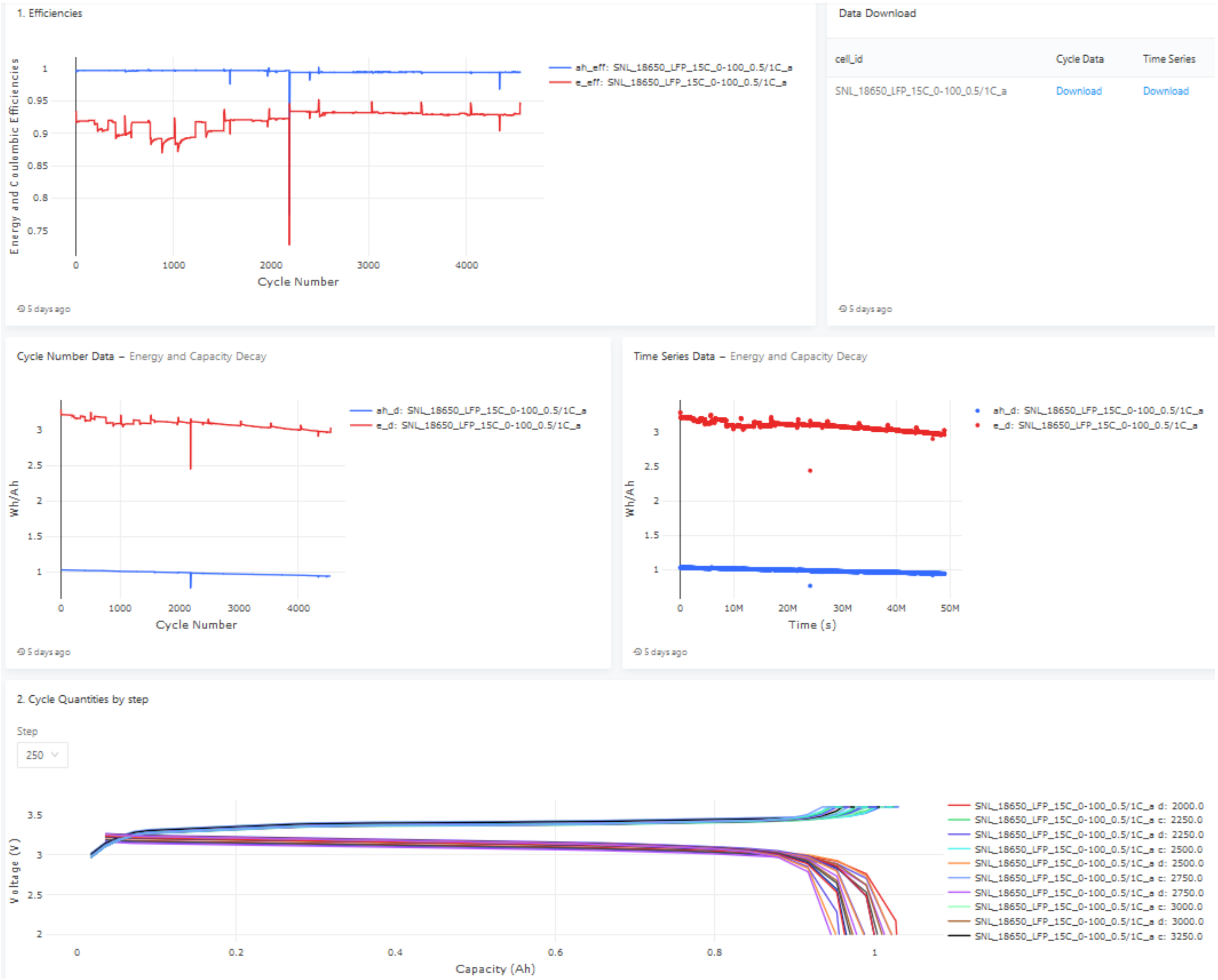
Battery data, modeling, and analysis tools

Electrical and Mechanical system

Control software

Data and analysis tools: battery archive and public data sets





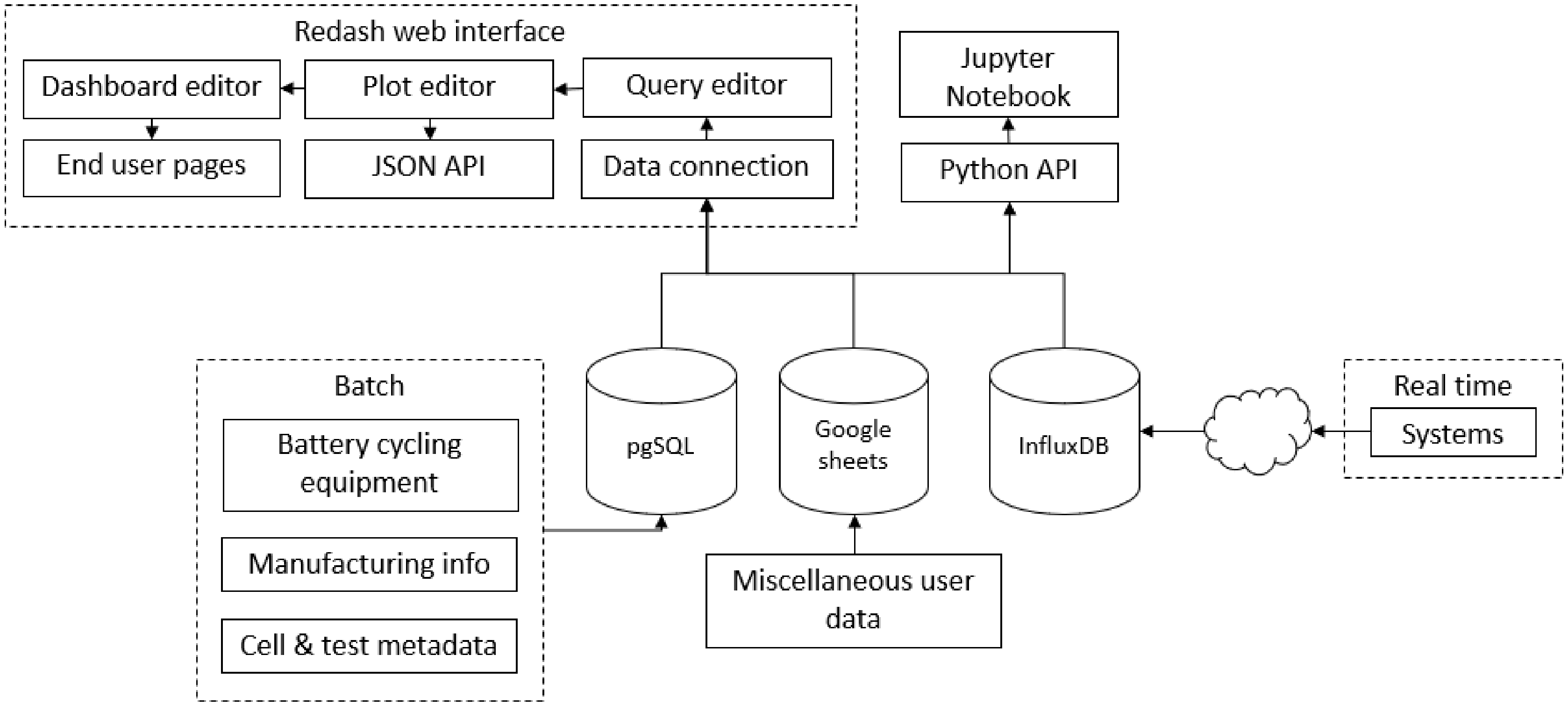
Broadest repository of public Li-ion testing data

- Used by manufacturers of energy storage systems, EVs, and consumer electronics
- Import data from different sources and convert to a common format
- Provide common battery visualizations
- Tests show how batteries behave when they are used for 1000's of charge and discharge cycles

Over 15,000 site users, many return visits, from over 50 countries, academia, and industry

Battery Archive runs on open-source software

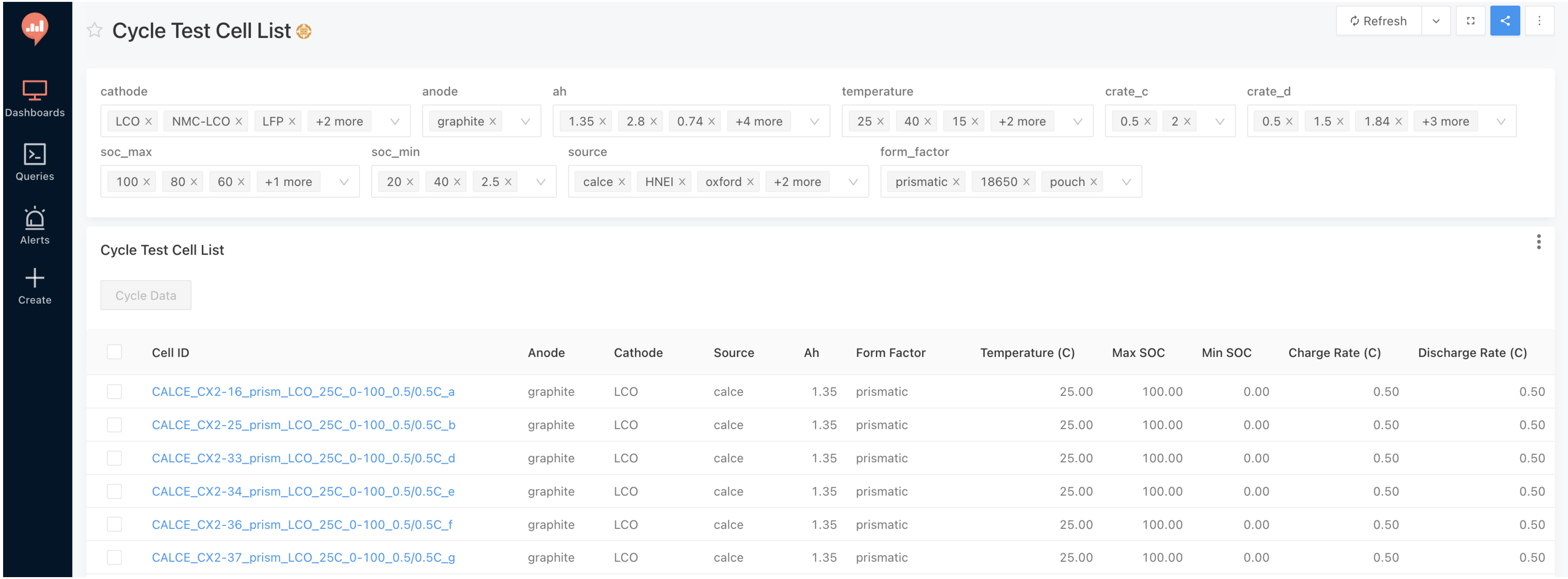
- Battery Archive is based on the Battery Lifecycle Framework (BLC) - BLC provides tools to visualize, analyze, and share battery data through the technology development cycle
- BLC has four components: (1) data importers, (2) one or more databases, (3) a front-end for querying the data and creating visualizations, (4) an application programming interface to process the data



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

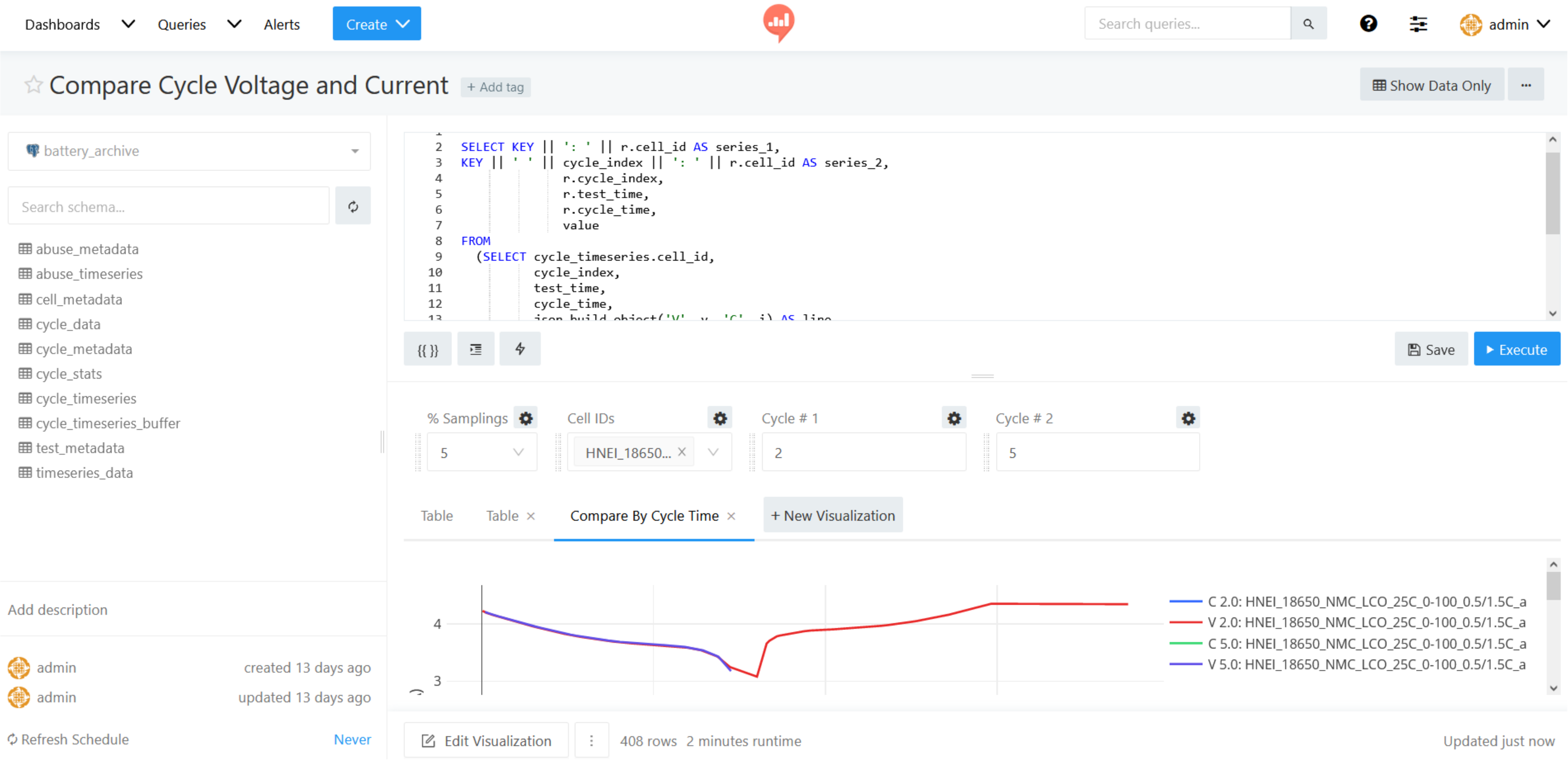
Redash – open source extract, transform, load software

Built a battery testing schema and a library of SQL queries (Go to project)

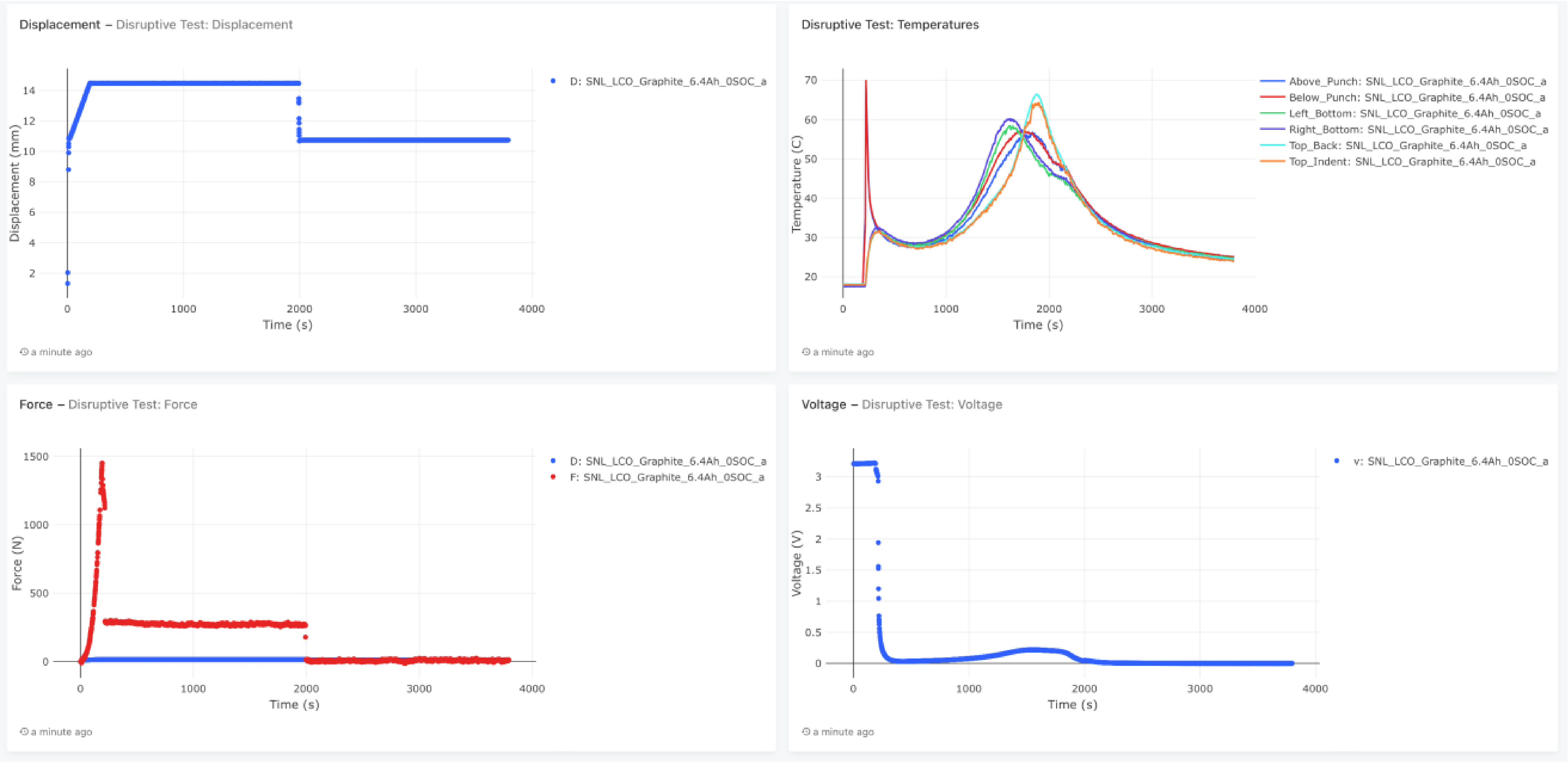


Cell ID	Anode	Cathode	Source	Ah	Form Factor	Temperature (C)	Max SOC	Min SOC	Charge Rate (C)	Discharge Rate (C)
CALCE_CX2-16_prism_LCO_25C_0-100_0.5/0.5C_a	graphite	LCO	calce	1.35	prismatic	25.00	100.00	0.00	0.50	0.50
CALCE_CX2-25_prism_LCO_25C_0-100_0.5/0.5C_b	graphite	LCO	calce	1.35	prismatic	25.00	100.00	0.00	0.50	0.50
CALCE_CX2-33_prism_LCO_25C_0-100_0.5/0.5C_d	graphite	LCO	calce	1.35	prismatic	25.00	100.00	0.00	0.50	0.50
CALCE_CX2-34_prism_LCO_25C_0-100_0.5/0.5C_e	graphite	LCO	calce	1.35	prismatic	25.00	100.00	0.00	0.50	0.50
CALCE_CX2-36_prism_LCO_25C_0-100_0.5/0.5C_f	graphite	LCO	calce	1.35	prismatic	25.00	100.00	0.00	0.50	0.50
CALCE_CX2-37_prism_LCO_25C_0-100_0.5/0.5C_g	graphite	LCO	calce	1.35	prismatic	25.00	100.00	0.00	0.50	0.50

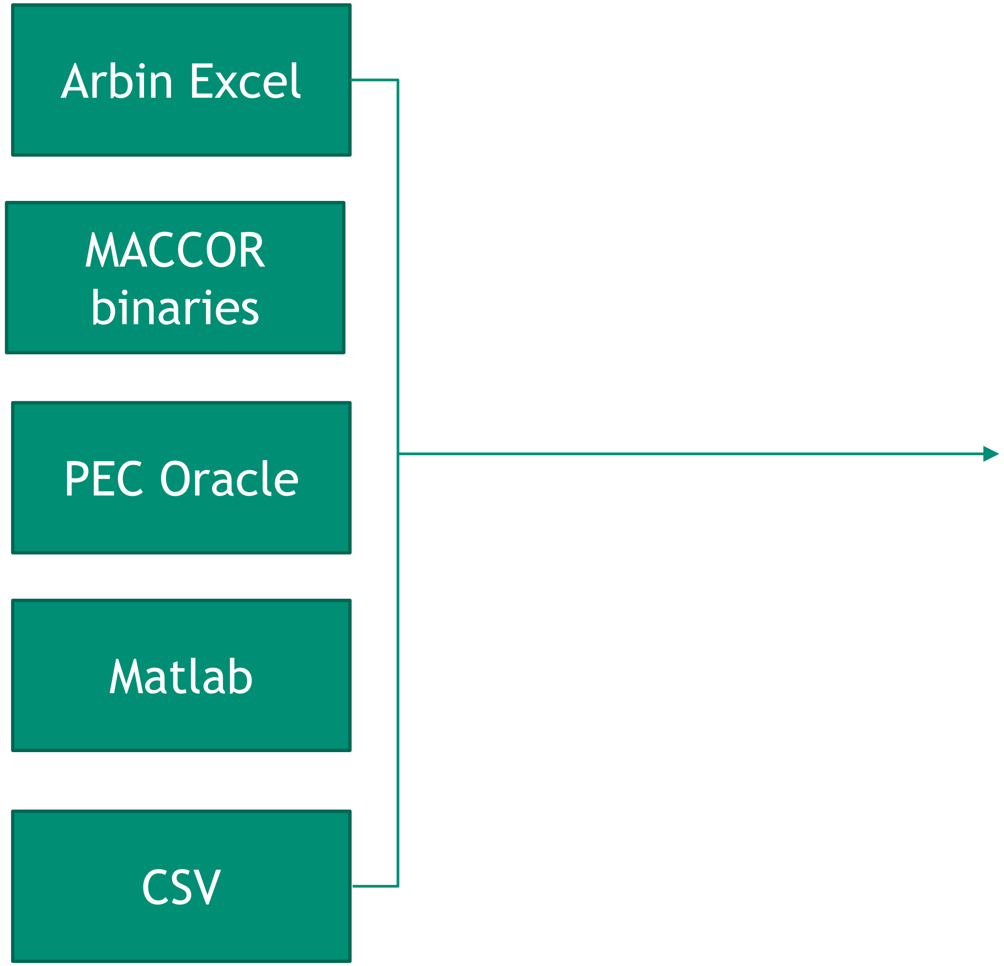
Researchers interact only with a web interface to browse and plot their data



Software readily extended beyond cycling data: Example nail penetration test



Publish data through open REST APIs in a standard format



{"ah":3.3,"anode":"graphite","cathode":"NCA","cell_id":"UL-PUR_CF15OV1C-1_pouch_NCA_25C_0-100_1/1C_e","dimensions":null,"form_factor":"pouch","source":"commercial","status":"completed","test":"cycle","tester":"arbin","weight":null},
{"ah":3.3,"anode":"graphite","cathode":"NCA","cell_id":"UL-PUR_CF10OV.3C-1_pouch_NCA_25C_0-100_1/1C_g","dimensions":null,"form_factor":"pouch","source":"commercial","status":"completed","test":"cycle","tester":"arbin","weight":null},
{"ah":3.3,"anode":"graphite","cathode":"NCA","cell_id":"UL-PUR_CF20OV1C-3_pouch_NCA_25C_0-100_1/1C_d","dimensions":null,"form_factor":"pouch","source":"commercial","status":"completed","test":"cycle","tester":"arbin","weight":null},
{"ah":3.3,"anode":"graphite","cathode":"NCA","cell_id":"UL-PUR_CF20OV1C-2_pouch_NCA_25C_0-100_1/1C_c","dimensions":null,"form_factor":"pouch","source":"commercial","status":"completed","test":"cycle","tester":"arbin","weig

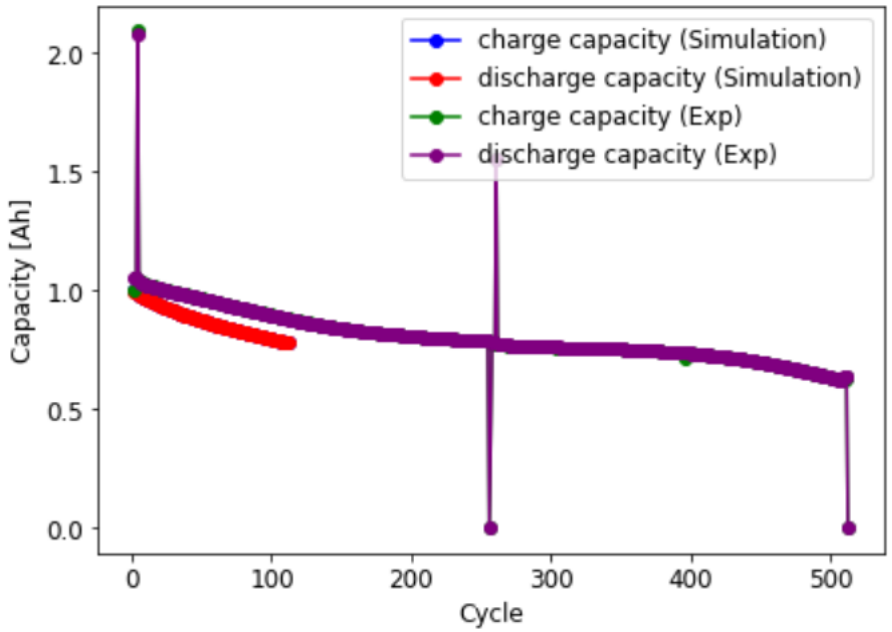
API Demo

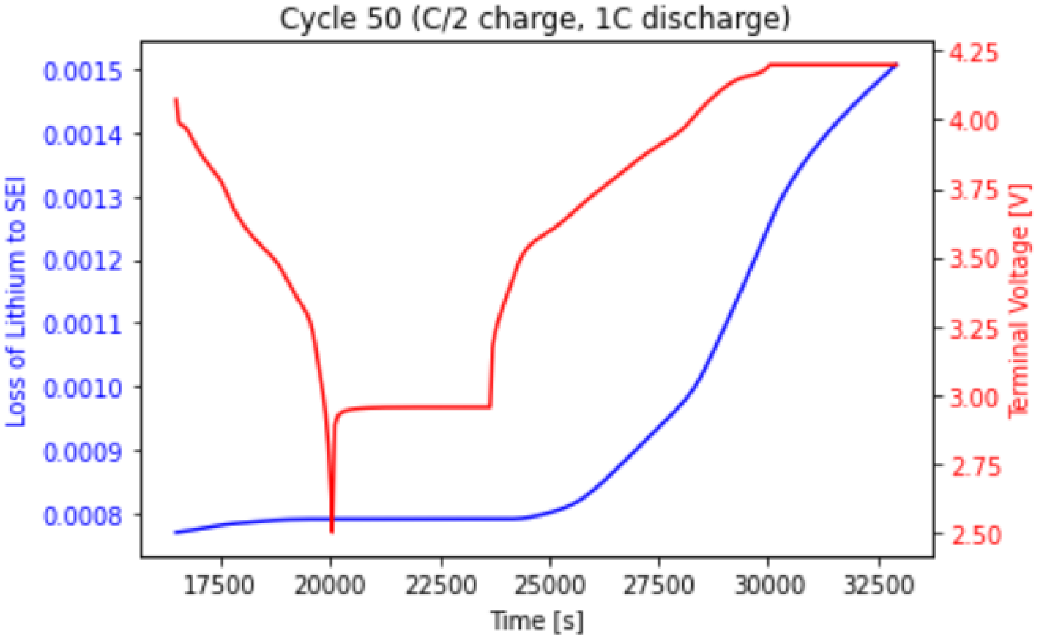
Compare with first-principle models

Open-source Python library (Faraday Institution) to solve physics-based electrochemical DAE models using DFN and SPM.

```
[ ]  pybamm.set_logging_level("NOTICE")

     ncycle = 500 # total number of cycles to run

     experiment = pybamm.Experiment([
         (f"Discharge at 1C until {Vmin}V",
          "Rest for 1 hour",
          f"Charge at C/2 until {Vmax}V",
          f"Hold at {Vmax}V until C/50"
         )
     ] * ncycle,
     termination="80% capacity"
     )
```

If we can understand degradation mechanisms, we can slow degradation with better charge control ([Demo](#))

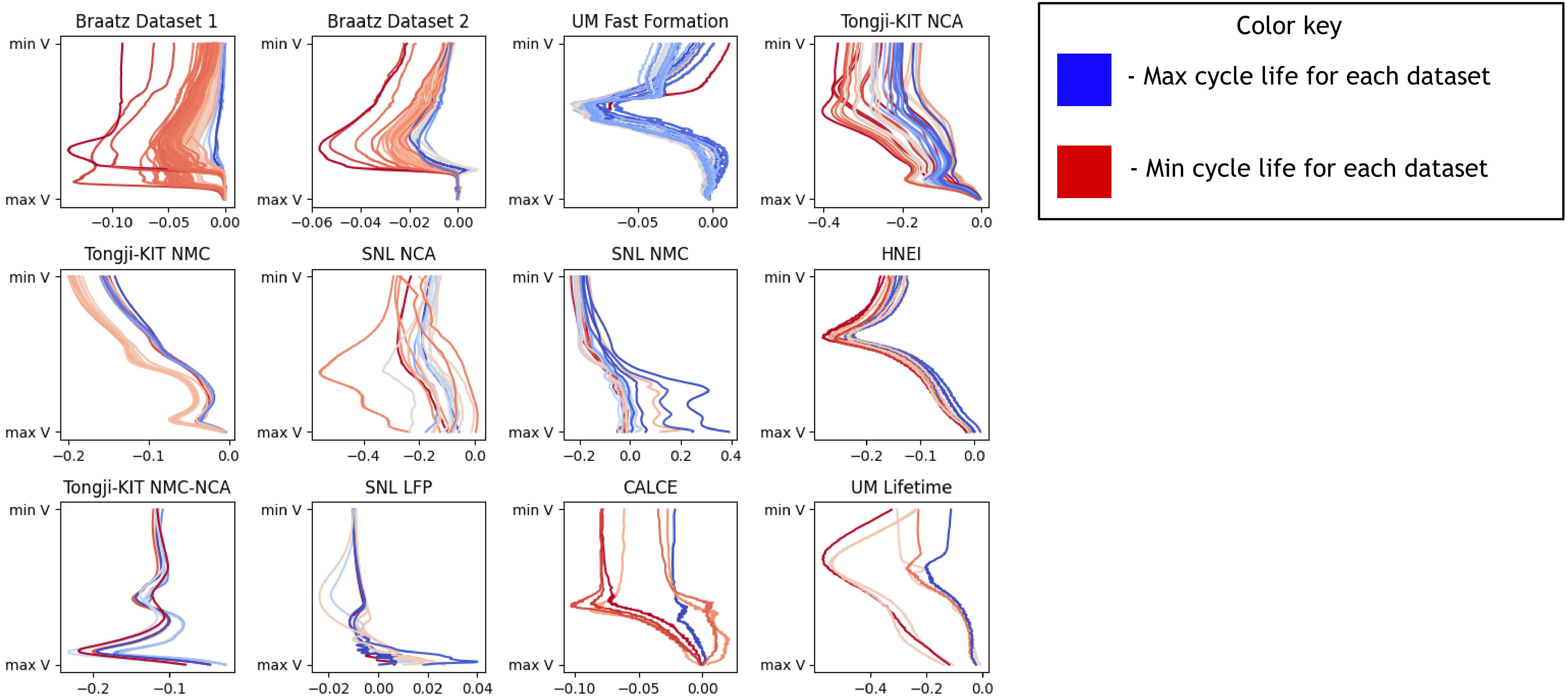




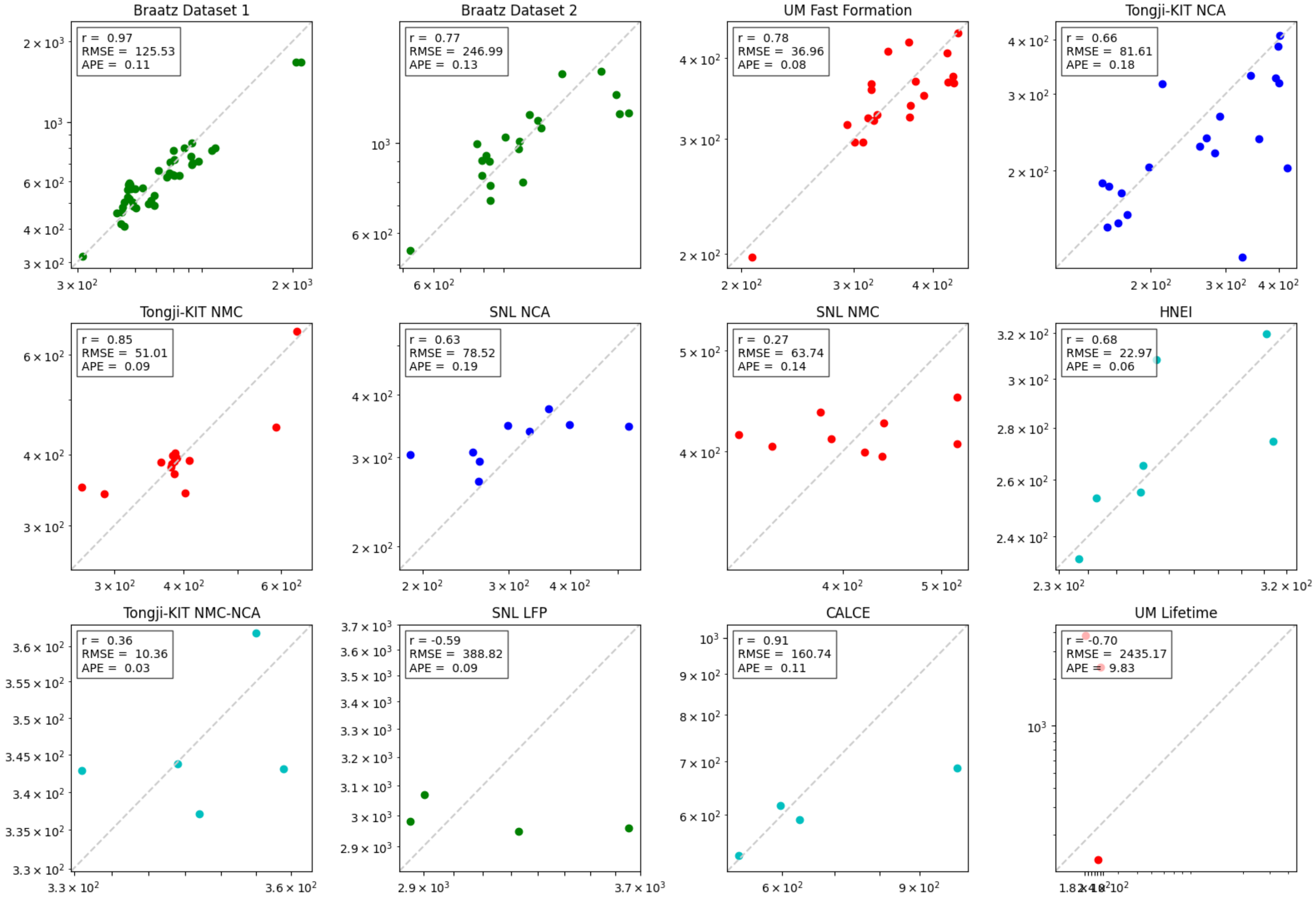
Sulzer, V., et. al. (2021). Journal of Open Research Software, 9(1).
https://github.com/pybamm-team/PyBaMM

Calculate advanced features in Jupyter Notebook

Plot of ΔQ for each data set ($\Delta Q = Q(V)_{100} - Q(V)_{10}$)

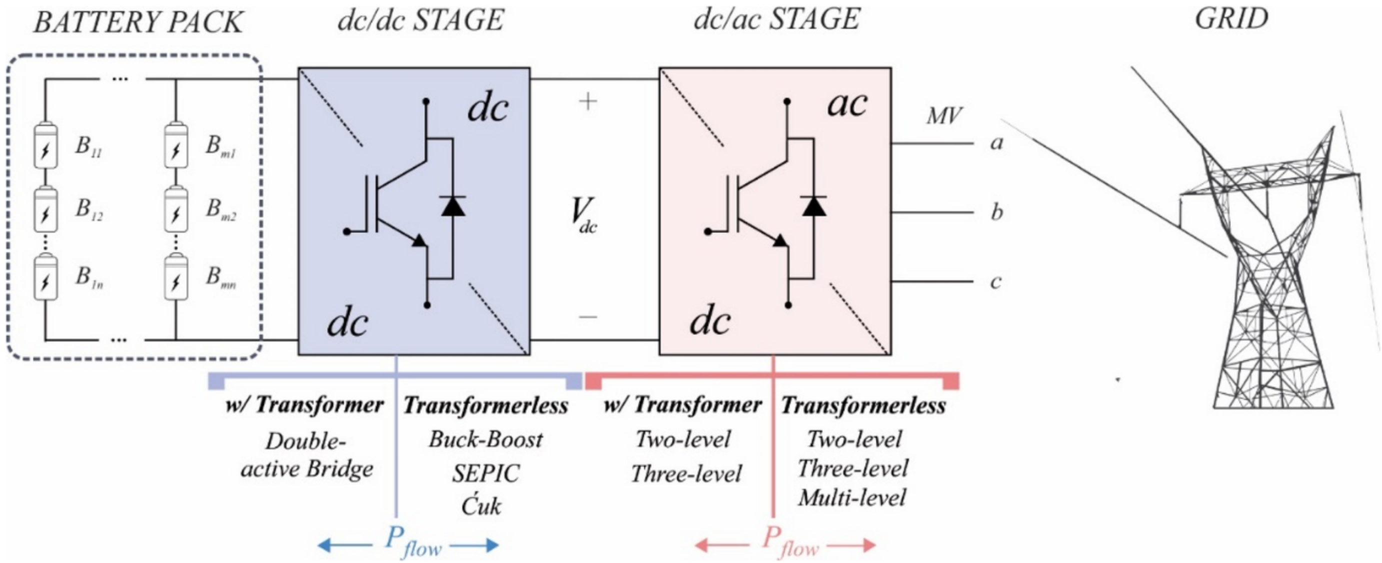


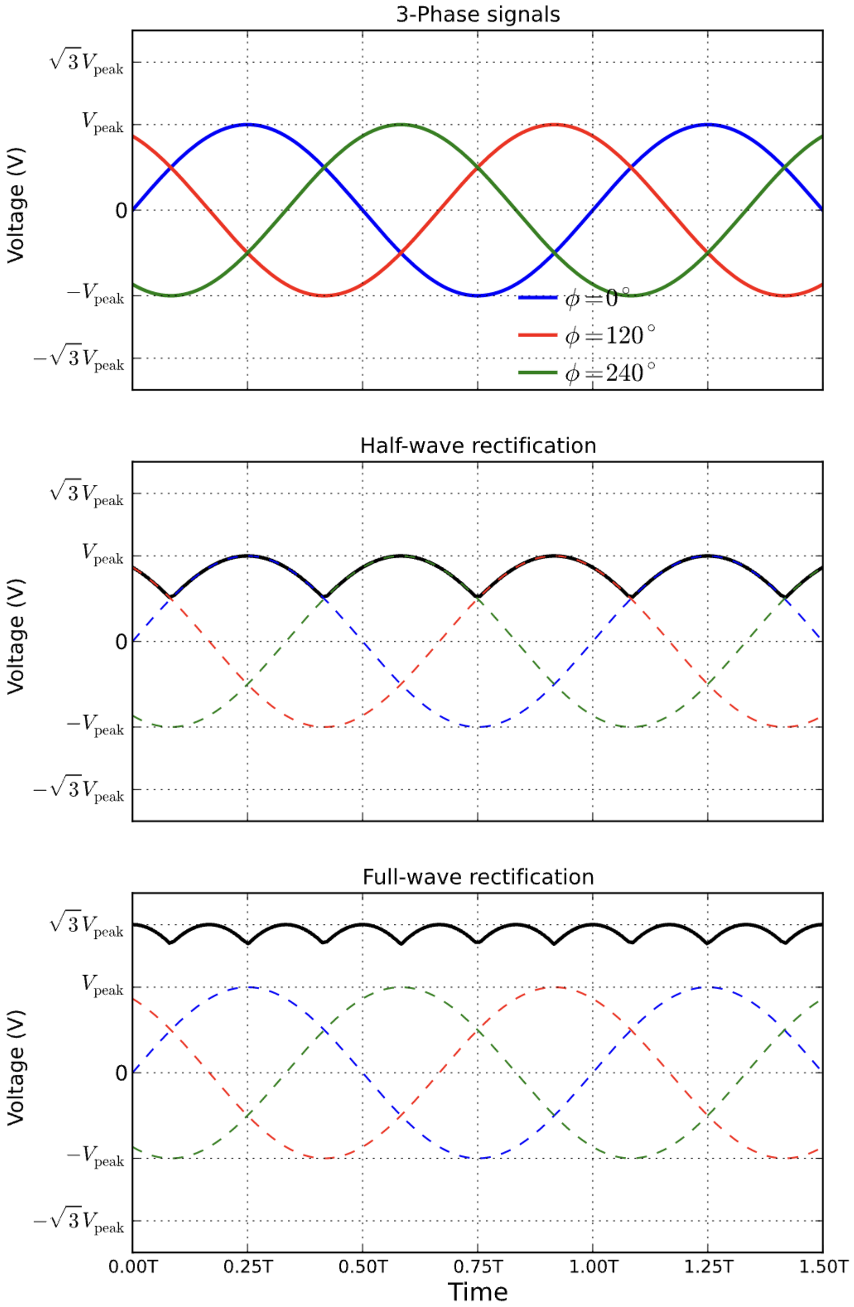
Predict cycle life using elastic net and data in Battery Archive



[Demo]

How does energy get from a battery to the grid?





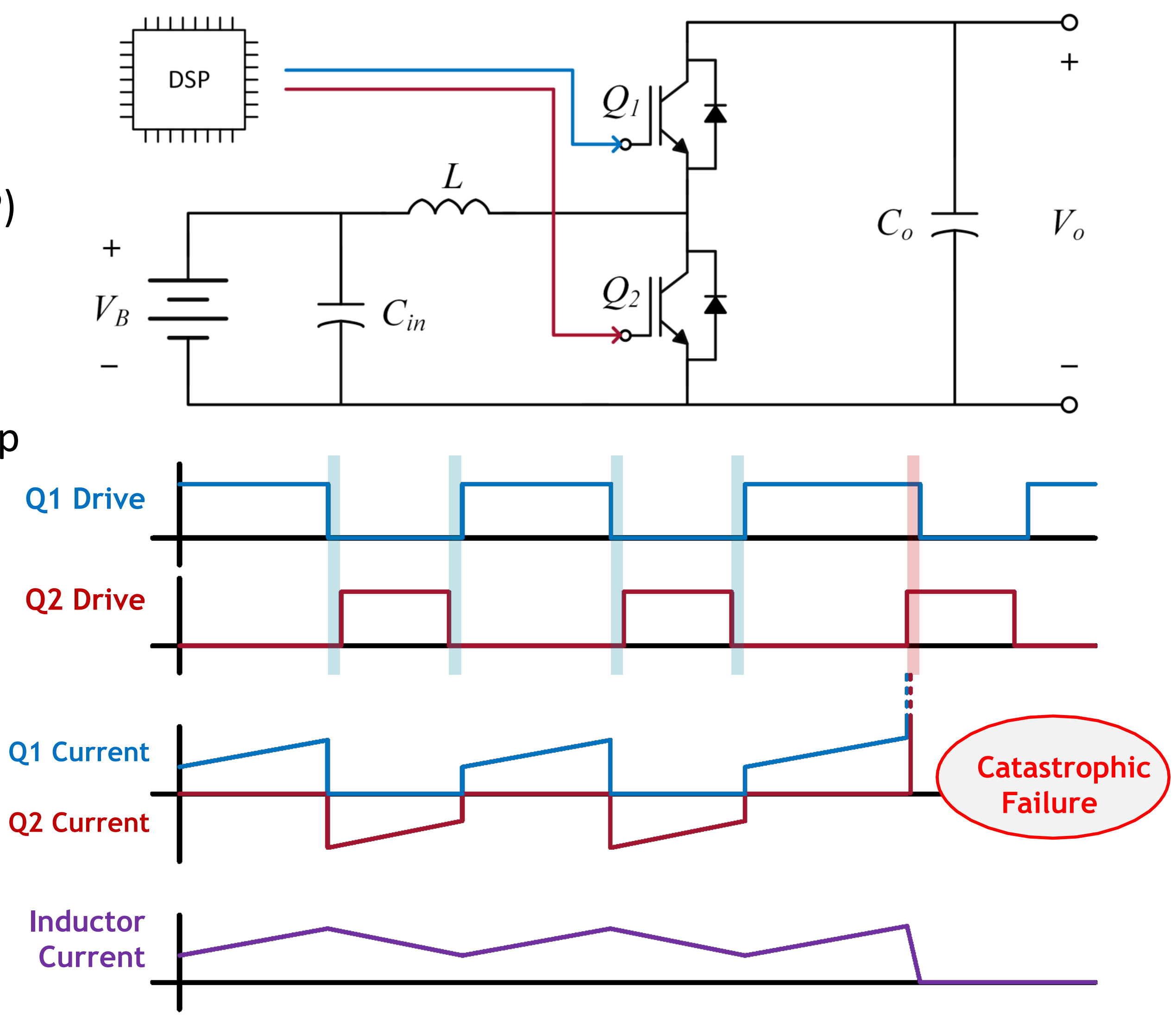
Challenges of gate-level control

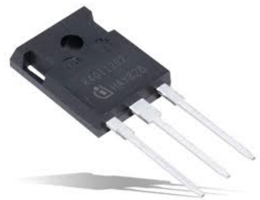
The basic building block

- DC-DC converter in battery charger application
- System is controlled by a digital signal processor (DSP)
- Drive signals for semiconductors Q1 and Q2 are complementary
- Turn-on and turn-off times are nonzero, so delays must be inserted into driver signals to prevent overlap

If a rising edge delay is applied, Q1 and Q2 will never be in the conductive on-state simultaneously.

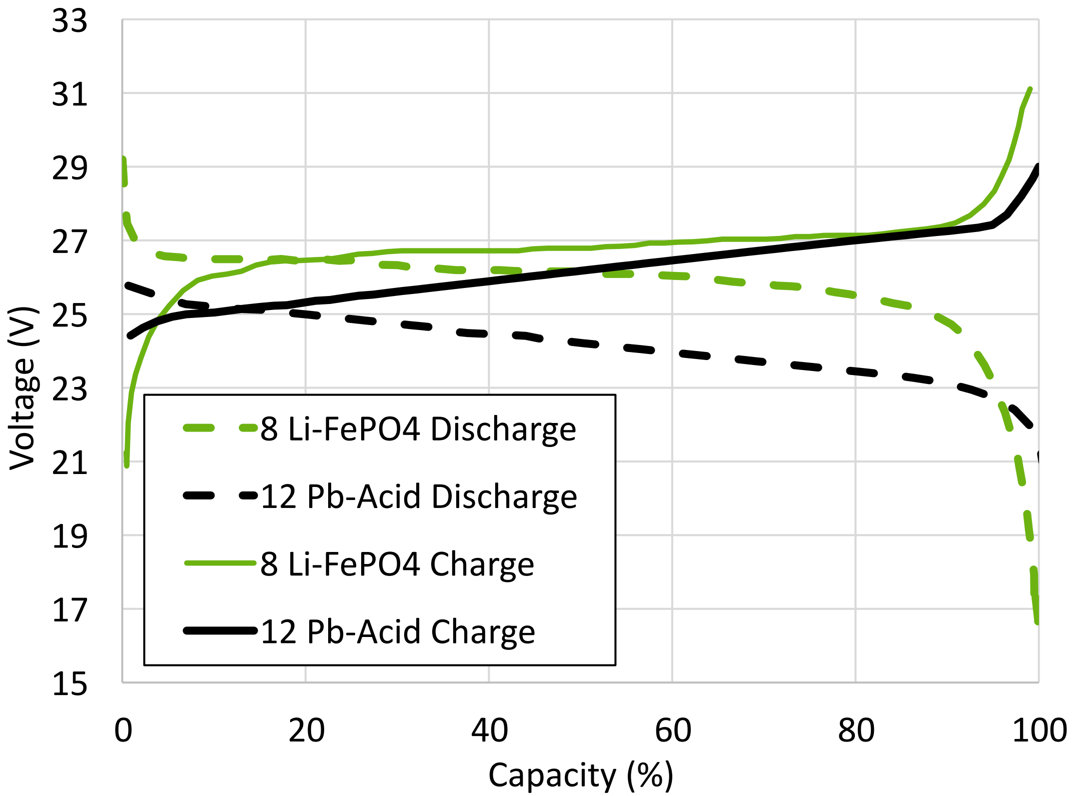
If a falling edge delay is applied, Q1 and Q2 will both conduct simultaneously, forming a short circuit across the output capacitor, likely causing irreversible damage to the converter.



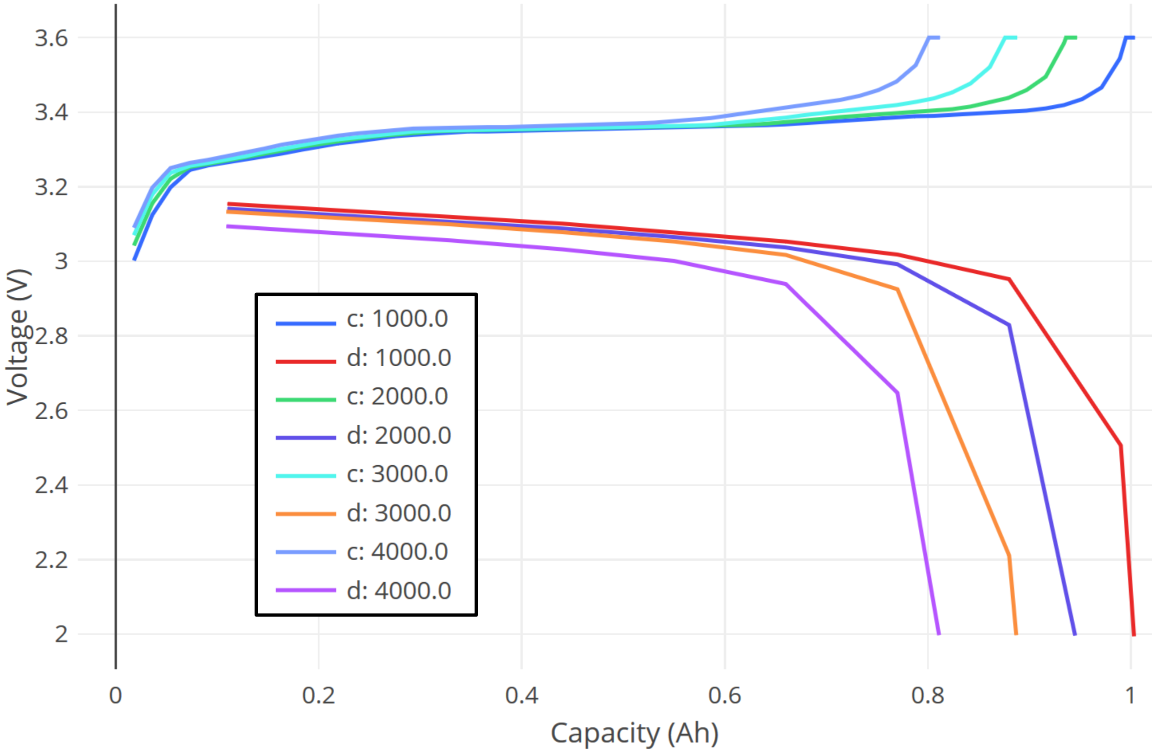


Challenges of managing batteries

Different types of batteries operate within different voltage limits
Some batteries have multiple voltage plateaus



Operating voltages change as cells age, so cell capacity cannot be replenished or extracted efficiently



LFP cells cycled with a 3C discharge and a 0.5C charge
Data from SNL www.batteryarchive.org

Batteries require different charging protocols

Battery type	Charge protocol
Li-ion	CC-CV-Rest
Lead-Acid	CC-CV-Rest-Float

CC -> Constant Current   CV -> Constant Voltage

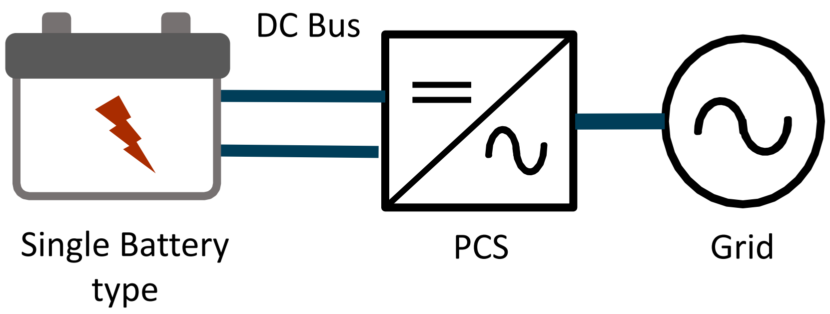
More complexity

- Discharge voltage depends on rate
- Charge/discharge voltage depends on temperature
- If overcharged, batteries will heat up and catch on fire!

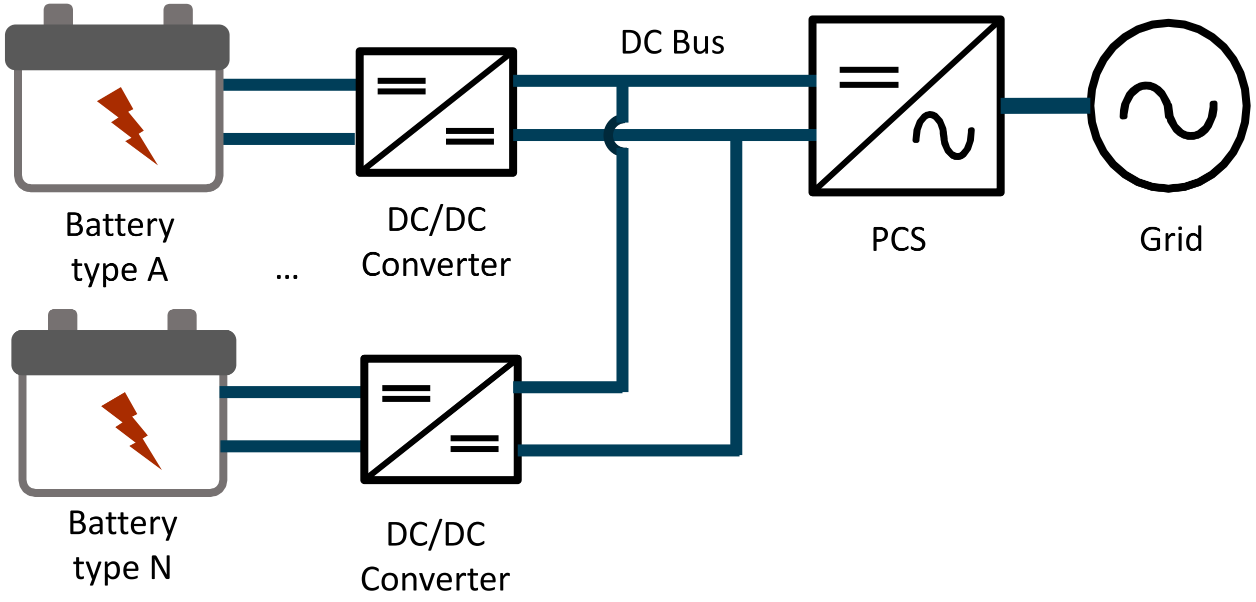
We selected a scalable and simple architecture to start

- Each controller can set a different charging current and cut off charging in different voltage limits.
- Aging batteries can be replaced without turning the string off.
- If one battery fails, all the other batteries can still be used (mix old and new batteries).
- The operating range of the batteries can be varied as cells age.

Traditional design

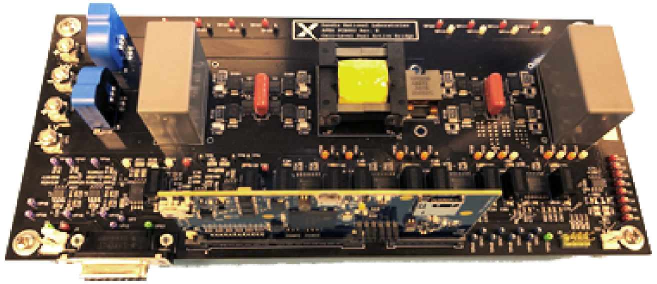


Flexible design

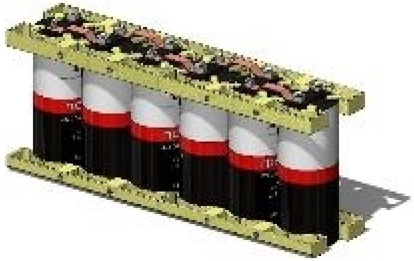


Hardware Platform: Modular system built to meet electrical standards

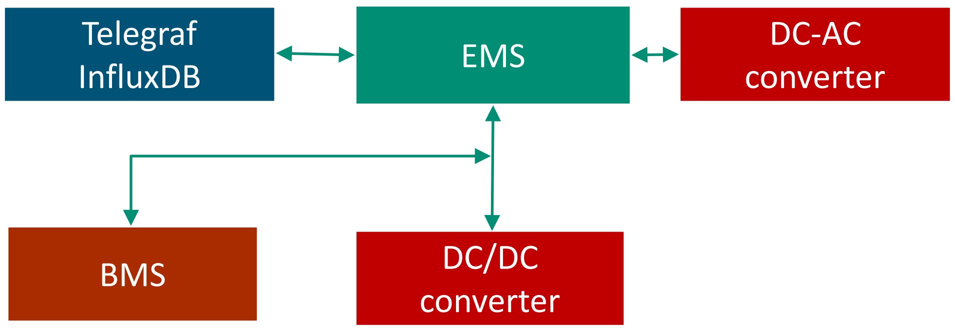
Synchronous Rectifier DC-DC converter



Dual-Active bridge



Developing open-source control software (end of 2023)



The basic building block

- BMS senses cell status and protects the battery
- EMS decides when to charge and discharge the battery to meet the needs of the application
- Communication protocols are serial, MODBUS, and CANBUS

Complexities

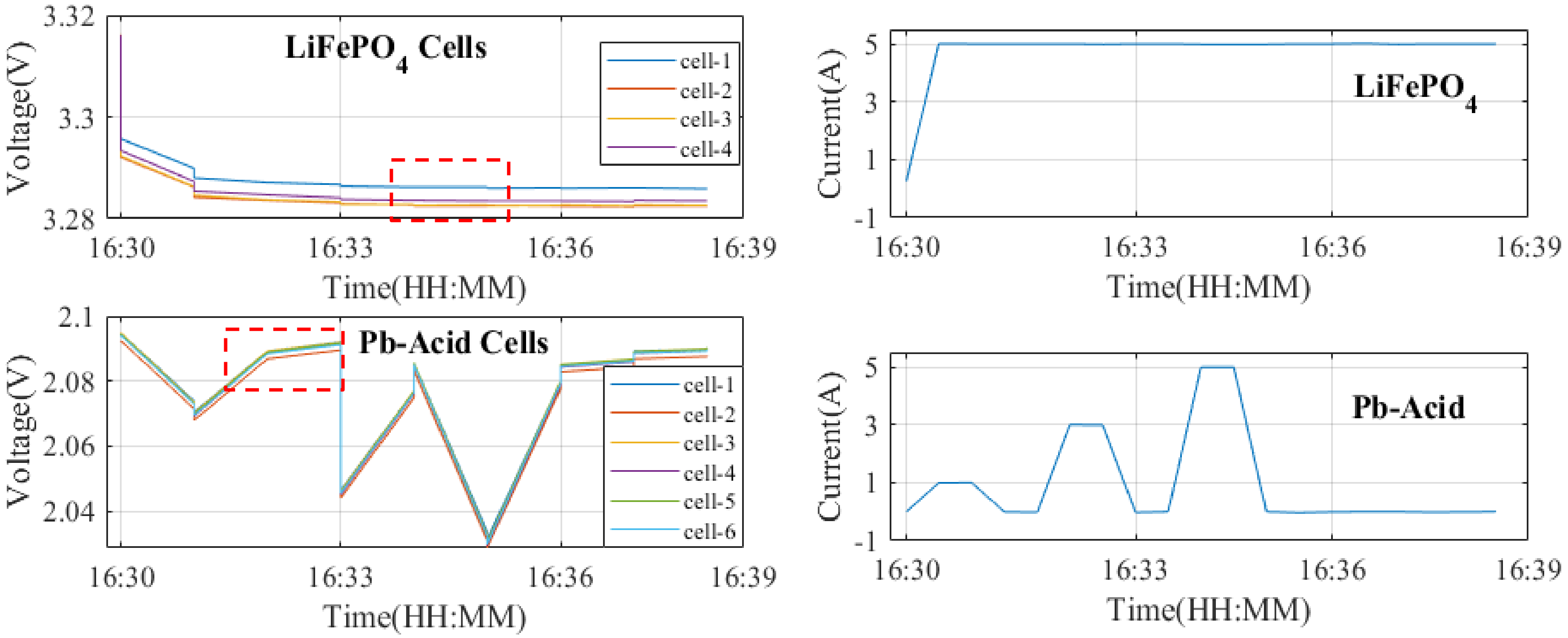
- No established standard among vendors
- Several cybersecurity risks to be addressed
- Software needs to be certified with the hardware

```
[DCAC]
Name = RPS

[Protocol]
Type = Loop
Charge = 95
Rest = 60
Discharge = 95

[COMMUNICATION]
communication_type = Serial

[BATTERY PACKS]
Packs = 1

[Pack_A]
Series = 4
Parallel= 1
CellName = PowerSonic
BMSModel = OrionBMS
CellType= LiFePO4
MaxCurrentCharge= 6.0
MaxCurrentDischarge= -6.0
Ah = 25
NomVoltage = 3.2
MaxVoltage= 3.65
MinVoltage= 2.54
MaxSoC= 95.0
MinSoC= 15.0
current = 1.0
DCDC = DAB
cell_voltages = 3.2
serial_port = COM8

[Pack_A_DAB]
conv_id = 1
serial_port = COM9

[Pack_B_DAB]
conv_id = 2
serial_port = COM7

[Data_Logger]
type = telegraf
sn
[RPS]
invtype = 208-3P
maxpowercharge = 125.0
maxpowerdischarge = -125.0
maxrampup = 20.0
maxrampdown = -20.0
hz = 60.0
t_env = 25
```

Operation of a system with a Li-ion and a Lead-acid pack

Decouple the operation of each battery pack

Pulse discharging of Pb-Acid and CC discharging of LiFePO4



- Pulse test is used for running quality control test on selected stacks.
- Cell to cell variations emerge quickly

Conclusions and future roadmap

Integrate open systems from data to mechanical systems

- Support battery companies
- Support power electronics component
- Provide data hubs and libraries of processing software
- Provide an ***SDK*** to companies and universities for use for their research
- Provide a platform to coalesce other DOE OE projects
- The activities prompt key fundamental research questions

To join the open-source projects, please contact vdeange@sandia.gov

Government grants may be available for specific projects

Acknowledgments

Funded by the U.S. Department of Energy, Office of Electricity, Energy Storage program. Dr. Imre Gyuk, Program Director.

Consortium of multiple labs, companies, and universities

Perspective

Principles of the Battery Data Genome

Logan Ward,[1] Susan Babinec,[1,*] Eric J. Dufek,[2,*] David A. Howey,[3,4,*] Venkatasubramanian Viswanathan,[5,*] Muratahan Aykol,[6] David A.C. Beck,[7] Benjamin Blaiszik,[1,8] Bor-Rong Chen,[2] George Crabtree,[1,9] Simon Clark,[10] Valerio De Angelis,[11] Philipp Dechent,[12,13] Matthieu Dubarry,[14] Erica E. Eggleton,[7] Donal P. Finegan,[15] Ian Foster,[1] Chirranjeevi Balaji Gopal,[6] Patrick K. Herring,[6] Victor W. Hu,[7] Noah H. Paulson,[1] Yuliya Preger,[11] Dirk Uwe-Sauer,[12,13] Kandler Smith,[15] Seth W. Snyder,[2] Shashank Sripad,[5] Tanvir R. Tanim,[2] and Linnette Teo[7]