NATIONAL RENEWABLE ENERGY LABORATORY

Behind-the-Meter Storage Overview

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National Renewable Energy Laboratory

Project ID # **elt235**

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Overview

Timeline

- October 1st 2018 - September 30th 2025.
- Percent complete: 10%

Budget

- Funding for FY 19: $2500K

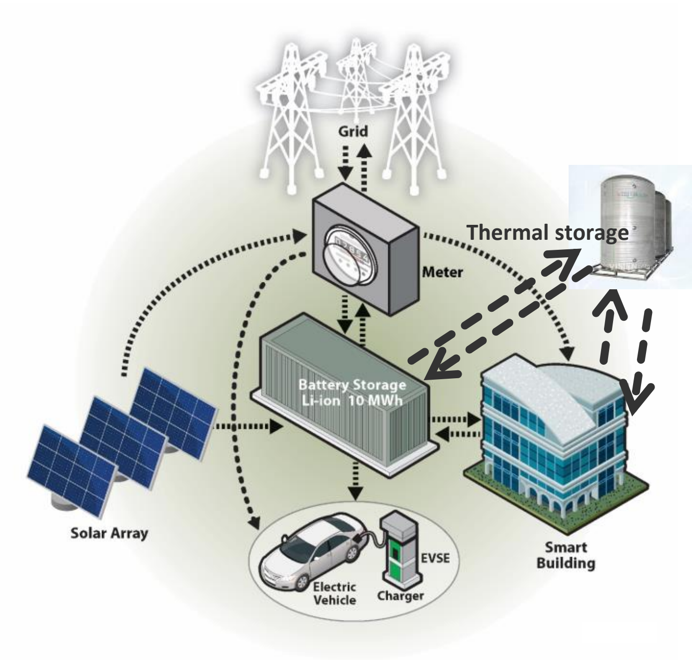
Barriers

- Development of stationary storage systems to enable extreme fast charging of EVs and energy efficient grid interactive buildings
  - Cost, Performance and Safety

Partners

- A joint project between VTO, BTO and SETO.
- Four Laboratory Team lead by NREL:
  - Sandia National Laboratory
  - Oak Ridge National Laboratory
  - Idaho National Laboratory

Behind-The-Meter Storage (BTMS)
Low TRL Work Guided by System Level Thinking.



- Focus on specific end user outcomes
- Minimize cost of energy to user
- Buildings are the largest electrical users.
- EVs will be charged at buildings.
- Demand charges need to be eliminated.
- Grid impacts minimized.
- Integration of PV is/will be common.

- Both electrons and heat need to be stored.
- New batteries are needed
- New thermal storage are needed

A partnership with the Buildings, Solar, and Vehicles Offices

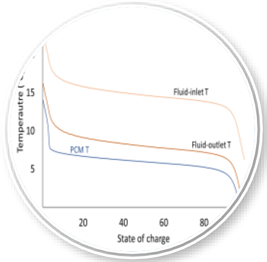
BTMS: Basic Premises

- **Technologically agnostic** in approach to storage systems (both electrochemical and thermal storage).
- All low TRL research will be guided by the system requirements.
- **Non-critical materials will be a foundation**.
- Current targets for vehicles will not lead to batteries that meet long-term storage requirements.
- Thermal storage and management will enable optimizing energy efficiency and minimizing cost in buildings applications.
- Testing of new materials in full systems will be the metric for success (safety, lifetime, energy density, and cost).
- This project takes advantage of the major investment the **VTO** Battery program has made in infrastructure, capabilities, and materials development coupled with the **BTO's** investments in thermal management and storage.
- Ongoing and integrated cost analysis will be essential to success.

Behind the meter storage (BTMS): synergies between battery and thermal energy storage

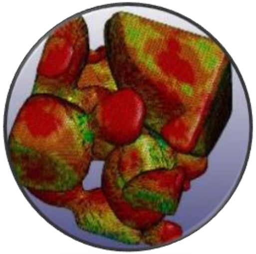
Metrics and target determination

Informing low-TRL R&D

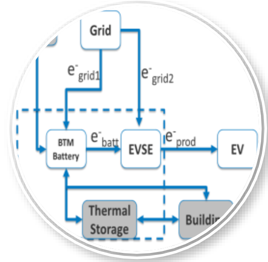


Multi-scale characterization

Materials to systems



Materials Discovery



Integrated-system modeling and design

strategies for battery + thermal storage systems

Full System Design

technology transfer activity where prototypes are produced for qualification

Integration experiments

Demonstrating controls and interoperability of technologies

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BTMS: FY19 Tasks

Task 1 will focus on the **development of metrics and targets for energy storage systems**, within the BTMS application space. The first and most important component of this research plan is the development of a realistic set of targets and metrics that will define success.

Task 2: BTMS Test Procedure Development & Verification
A critical component of any materials and device development is understanding how the research relates to the state-of-the-art and the quantification of research progress. In addition, the final device outcomes must be assessed in a total-systems configuration. This requires a **well-designed set of test procedures that allows for specific milestones and go/no-go decisions**.

Task 3: Battery Material and Cell Design Optimization for BTMS – Battery Storage Technology R&D
To meet the targets of $100/kWh, 8000 cycles, and 20-year lifetimes, **we must look to safe cell chemistries that use abundant materials and provide long calendar life, cycle life with at least a 4-hour discharge duration, and low cost**. As secondary design parameters, we will consider overall energy density and temperature range performance. **(to begin Q4 FY19)**

BTMS: Milestones VTO

- Q1: Create database or catalogue of historically evaluated critical-materials-free batteries to establish baseline on current state-of-art.
- Q2: Purchase commercial cells or cell materials.
- Q2: Establish initial protocols and testing procedures to be validated by commercial material cells.
- Q3: Establish preliminary targets and baseline sensitivity analysis for system cost to be published (AMR).
- Q4: Commercial material cells on test.
- Q4: Completed the component evaluations and identified the initial research priorities for performance enhancements for both system- and cell-level components.

Metrics and target determination: VTO Fast Charging

Battery Storage (DRAFT): **1–10 MWh** systems at **$100/kWh** able to cycle **2x/day** with a **4-h discharge** and lifetime of **20 yrs** and **8.000 cycles**

Clearly these are very high-level targets, and a major effort in FY19 will be to define the specific targets for BTMS for fast-charging and GEB applications.

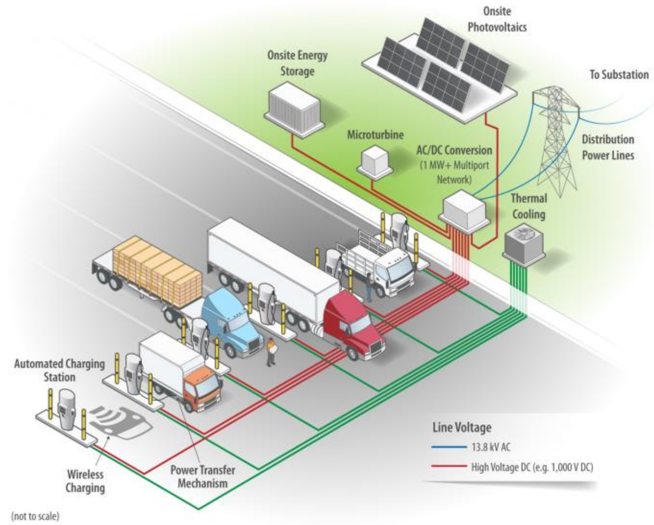
Chemistry will dominate lifetime, power, and energy.

Balance-of-plant issues may dominate cost.

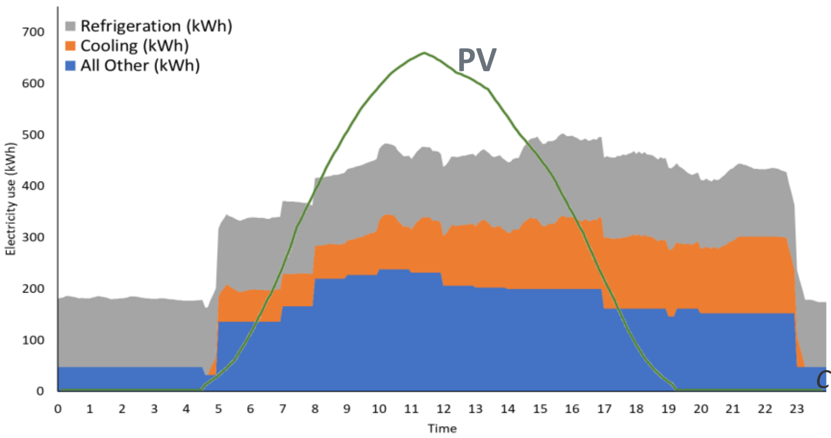
Thermal management of high-power systems will need to be considered.

Must minimize grid impacts.

No use of critical materials!



Metrics and target determination: Big-box grocery store – electrical + thermal load



Chicago, IL
July

Building energy efficiency will require optimizing storage, load (including EV fast charging) and generation in a grid connected building with a dynamic rate structure for electricity supplied by a renewable dominated grid. How do we balance thermal and electrical loads in a cost effect fashion.

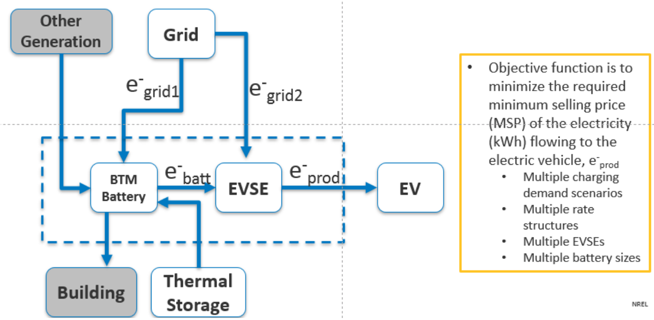
Metrics and target determination

Overall Metrics are very high level ($100/kWh, 8000 cycles, and 20-year lifetimes) and need to be refined into more specific targets.

- What are the application-specific power requirements?
- What is the actual cyclic needs for a specific application (4-hour time shift vs multiple EV fast-charging at commercial station)?
- How can the coupling of thermal and electrical energy allow for mixing of power and energy in a given application.
- What is needed from a thermal storage material to optimize for using/mitigating the heat from EV fast-charging or allowing for downsizing of the electrical energy storage in building loads?
- How does time-of-use pricing affect the storage requirements?
- What are the cost savings from elimination grid interconnect upgrades?

Metrics and target determination: Cost Modeling Overview for EVSE and Battery Storage System

System Boundary Being Modelled



- Objective function is to minimize the required minimum selling price (MSP) of the electricity (kWh) flowing to the electric vehicle, e^-_{prod}
  - Multiple charging demand scenarios
  - Multiple rate structures
  - Multiple EVSEs
  - Multiple battery sizes

Purpose:

- Quantify benefits of battery storage at EV charging stations
- Define the highest cost inputs and quantify the impacts of research accomplishments and goals
- Expansion to buildings and thermal storage will follow in Fy20

Utility Rate database used to quantify rates

- Energy, Demand, Fixed Fees

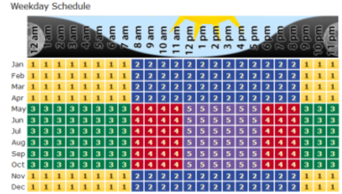
Tiered Energy Usage Charge Structure

Period	Tier	Max Usage	Max Usage Units	Rate $/kWh	Adjustmen
1	1		kWh	0.08684	
2	1		kWh	0.10163	
3	1		kWh	0.08012	
4	1		kWh	0.10749	
5	1		kWh	0.15199	

Fuel Adjustments Monthly ($/kWh)

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec

Weekday Schedule



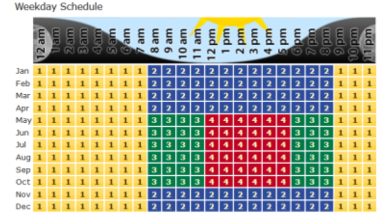
Seasonal/Monthly Demand Charge Structure

Period	Tier	Max kW Usage	Rate $/kW	Adjustments $/kW	Jan
1	1		15.97		•

Time of Use Demand Charge Structure

Period	Tier	Max kW Usage	Rate $/kW	Adjustments $/kW
1	1		0	
2	1		0.13	
3	1		5.45	
4	1		20.62	

Weekday Schedule



Analysis of costs and opportunities are based upon current data and existing components which will then enable identification of research opportunities and prioritize research investment.

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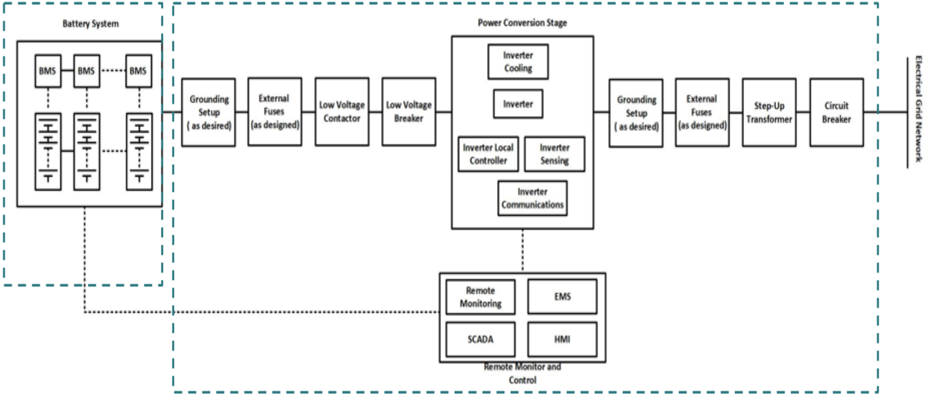
Metrics and target determination: Review of Energy Storage components and the modeled cost ranges based on a standard configuration

- Bottom up construct model approach analyses the cost contribution of each system component.
- These costs are obtained from commercial and research subject matter experts, literature review, and detailed equipment quotations.
- Each equipment component and subcomponent cost varies with size and system design. This high level overview shows the estimated values used in the modeled analysis.

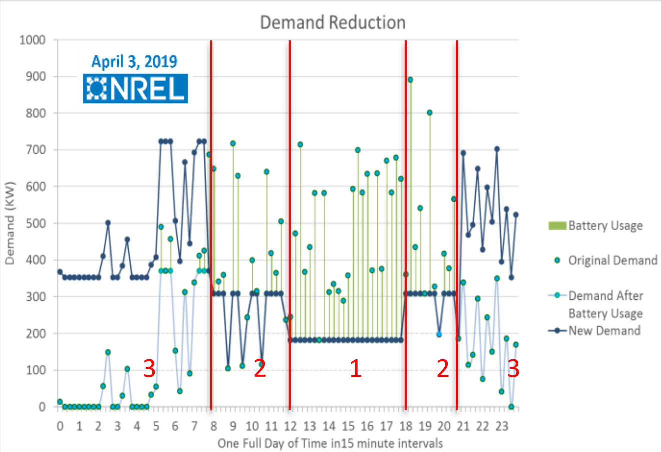
BESS PE Installation Components	Estimated Total Cost ($)	Estimated Rate ($/W)
Power Conversion System	70,000 – 120,000	0.07-0.12
Structural Balance of System	40,000 – 90,000	0.04-0.09
Electrical Balance of System	50,000 – 150,000	0.05-0.15
Engineering Procurement & Construction	50,000 – 150,000	0.05-0.15
Soft Cost	80,000 – 190,000	0.08-0.19

Cost Estimate for a 1 MW, 13.8 kV_{ac} setup:

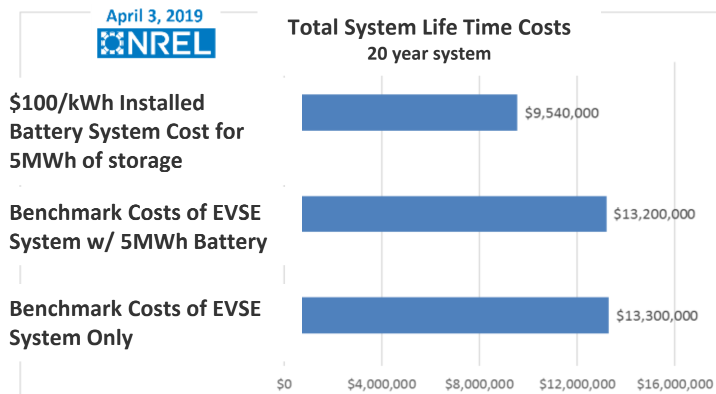
	Estimated Cost ($)	Estimated Rate ($/W)
Total BESS PE Installation	290,000 – 700,000	0.29-0.70



Metrics and target determination: Adjusted Energy Demand and Modeled Life Time System Costs



The target of $100/kWh battery installation cost results in **27%** reduction compared to current costs



Models chooses least cost source of electricity based on **load scenario** and electricity **rate structures** by location

Even at todays costs batteries as buffers for the grid are cost effective if $100/kWh are achieved significant cost savings are realized. However, doing this with critical materials free systems that have 20-30 year lifetimes will require significant research.

Multi-scale characterization
- Baseline Assessment of Cells

Testing approach evolves in parallel with BTMS system refinement

- Define baseline operating scenario
- Develop preliminary performance & life tests
- Benchmark and Age commercial cells under preliminary procedures
- Evaluate degradation mechanisms to help refine candidate technologies
- Update performance & life tests to match refined targets

Six 350kW DCFC units supported by 1 MWh ESS

Accelerated Cycle & Calendar Aging

- 55°C Calendar at 100% SOC
- 1C/Imax Full Charge/Discharge Cycling at 10,30,45°C
- 0.5C/0.5C Full Charge/Discharge Cycling at 30°C
- 0.5C/1C Full Charge/Discharge Cycling at 30°C
- 0.5C/0.5C Shallow Charge/Discharge Cycling at 30°C

Discharge Capacity, HPPC, and Differential Capacity Tests

Cell Types Chosen for Preliminary Aging/Testing

- LFP/Gr
- NMC/LTO
- NMC/Gr

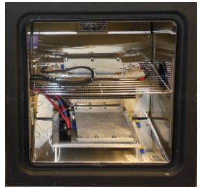
Cell Modeling & Diagnostics

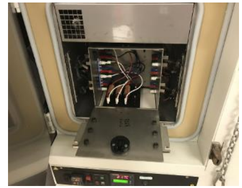
- Investigate candidate couples and ability to tune to BTMS targets using ANL BatPaC
- Investigate degradation using diagnostic techniques to identify likely degradation mechanisms

The current testing protocols are designed to determine the limits of current systems and help plot a research agenda. .

Multi-scale characterization: Technical Accomplishments and Progress

Baseline cells procured
- Fixtures fabricated
- Setup completed

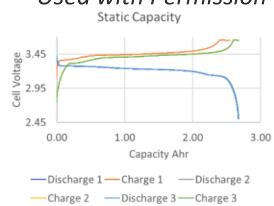


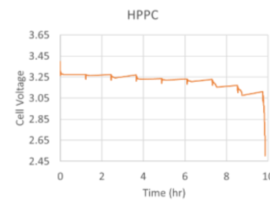


Photos: Matt Shirk/INL, Brian Perdue, SNL Used with Permission

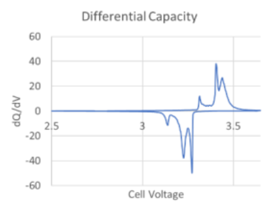
Preliminary testing & aging methods executed on 3 cell types
- 7 conditions for each type are running at INL and SNL

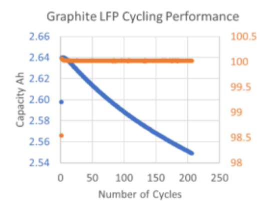
BOL test data processed and provided to feed analysis
- Energy density and Specific Energy





BatPac Analysis begun to investigate opportunities to optimize cell design for BTMS application for several critical material free couples

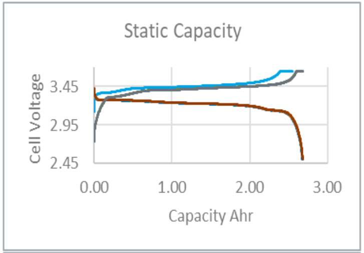


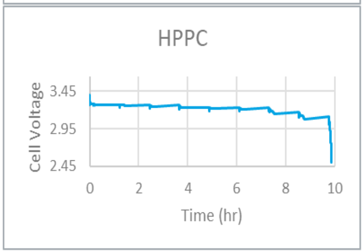


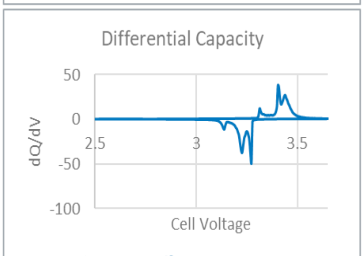
Review of CM free commercial cells for next round of testing underway

Testing is underway

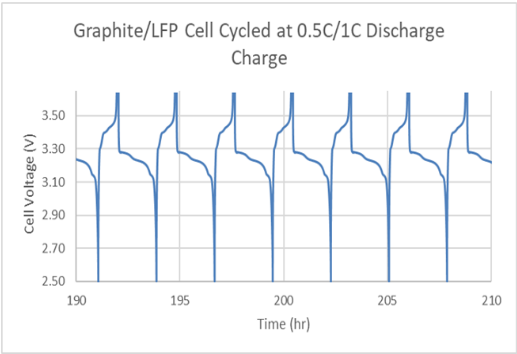
Multi-scale characterization: Technical Accomplishments and Progress

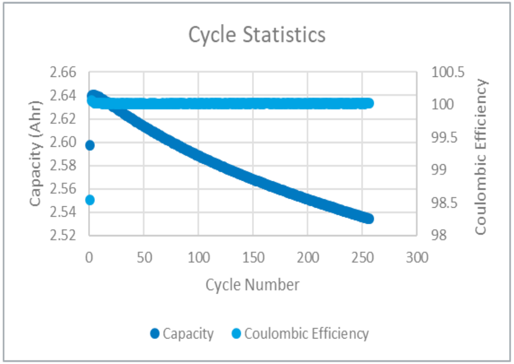






32 Days of Continuous Cycling

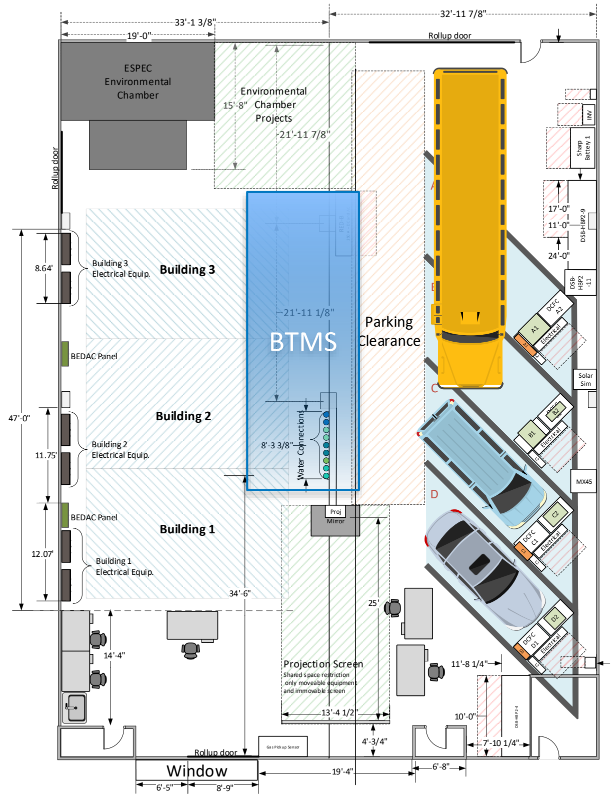




In Process!

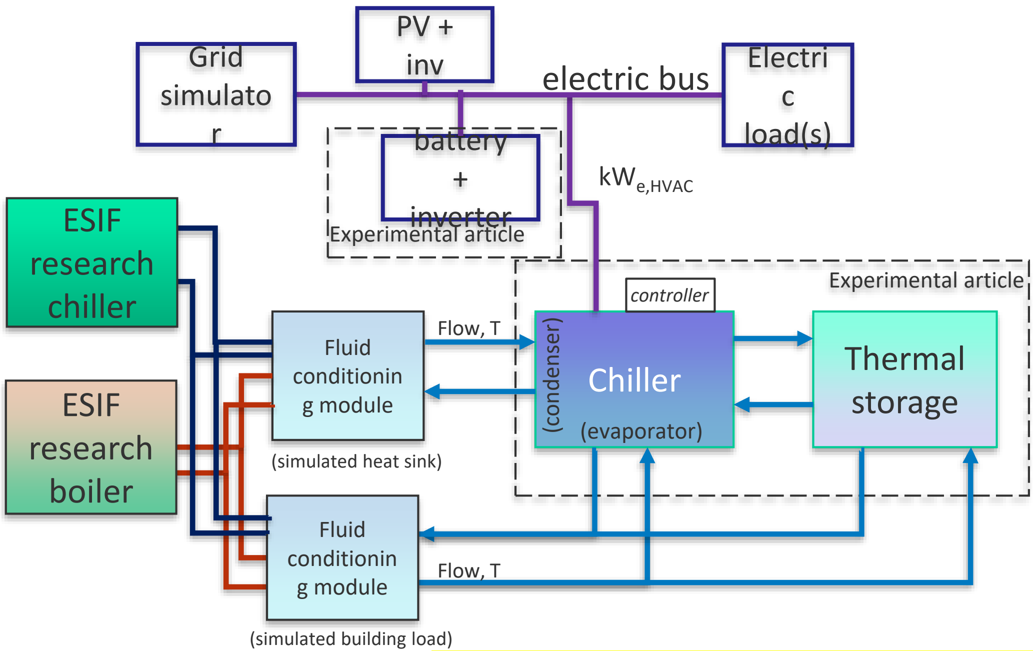
Integrated-system: OCL- Buildings - Electric Vehicle Integration

- Space will be available for evaluation of charging system for large MD vehicles.
- OCL Connection to other labs in ESIF
  - 2x 250A AC RED-B (2nd in process)
  - 2x 250A DC RED-B (2nd in process)
  - 1x 1600A AC RED-B (in process)
- Commercial Building Integration
  - 1600A AC (in process)
  - 2x 250A DC (2nd in process)



New integrated research facility is under construction at ESIF.

Integrated-system: Thermal Energy Storage and Electrochemical Integration Lab



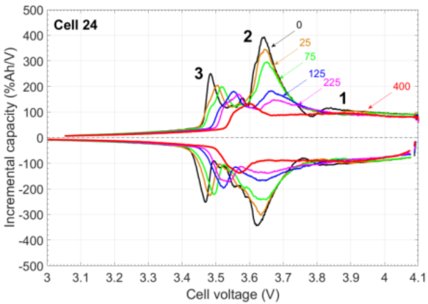
Experimental articles:

- Chiller + TES
- Heat pump + TES
- Thermal storage module
- Thermal storage material
- Electrochemical storage
- System controller
- Supervisory controller

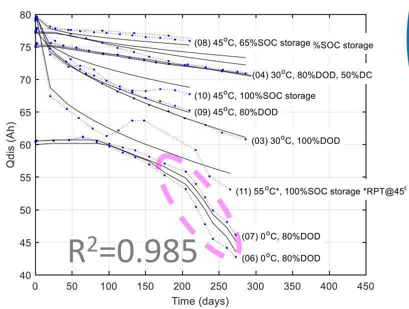
Part of the new research facility is designed to understand the synergies, necessary controls and opportunities that combined thermal and electrochemical energy storage provide.

Machine learning to advance accelerated cycle life prediction

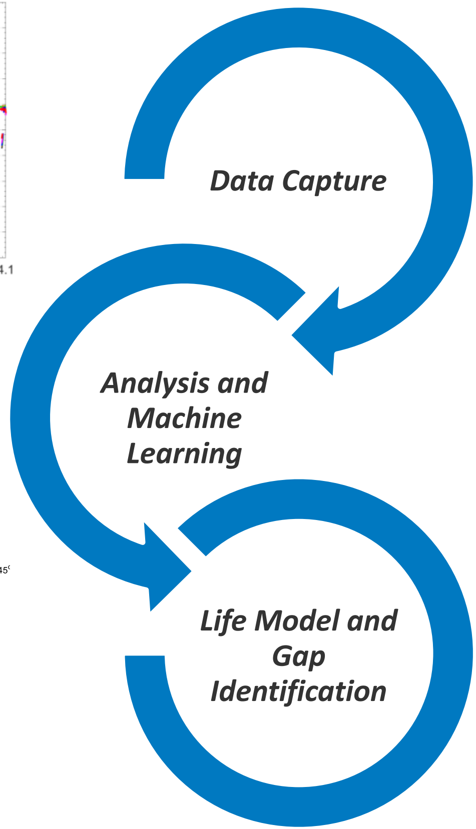
Aligning accelerated cycle life evaluation, analysis and life modeling



Failure mode progression



Life modeling



Data and sensitivity analysis

Life prediction for long term storage under widely varying use profiles will be needed. (>20 year lifetime).

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A “Universal” Physics-Based Life Model is Needed to Predict Chemistry/C-rate/DOD Life-Dependence

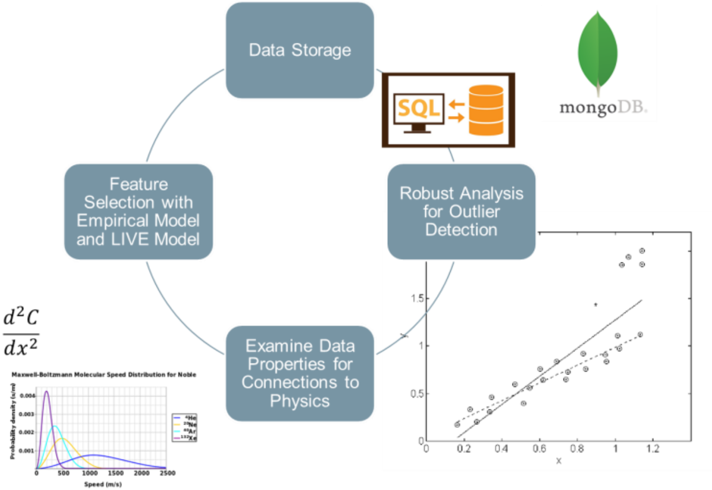
Physics-Based Approach

- Incorporates discrete aging of the system include failure modes, rates and use profiles
- Combination of Local, Rate and Global models

$$\epsilon_b \frac{dC}{dt} = D\frac{d^2C}{dx^2}$$

Mechanism	Trajectory equation	State equation	Parameters
Diffusion-controlled reaction	$x(t) = kt^{1/2}$	$\dot{x}(t) = \frac{k}{2}\left(\frac{k}{x(t)}\right)$	k – rate ($p=1/2$)
Kinetic-controlled reaction	$x(t) = kt$	$\dot{x}(t) = k$	k – rate ($p=1$)
Mixed diffusion/kinetic	$x(t) = kt^p$	$\dot{x}(t) = kp\left(\frac{k}{x(t)}\right)^{\left(\frac{1-p}{p}\right)}$	k – rate, p – order, $0.3<p<1$
Diffusion controlled reaction with mechanical damage	See Appendix A	$\dot{D} = \frac{dN}{dt} k_D \cdot (\sqrt{D})^p$ $\dot{x}_0(t) = \frac{k}{2}\left(\frac{k}{x(t)}\right)$ $\dot{x}_j(t) = D\frac{k}{2}\left(\frac{k}{x(t)}\right)$	k – rate, p – order
Cyclic fade – linear	$x(N) = kN$	$\dot{x}(N) = k$	k – rate ($p=0$)
Cyclic fade – accelerating.	$x(N) = \left[x_0^{1+p} + kx_0^p(1+p)N\right]^{\frac{1}{1+p}}$	$\dot{x}(N) = k\left(\frac{x_0}{x(N)}\right)^p$	k – rate, p – order, $0 \geq p > 3$
Break-in process	$x(t) = M(1-\exp(-kt))$ or $x(N) = \ldots$	$\dot{x}(t) = k(M - x(t))$	M – maximum fade, k – rate
Sigmoidal reaction	$x(t) = M\left[1 - \frac{2}{1+\exp(kt^p)}\right]$ or $x(N) = \ldots$	$\dot{x}(t) = \frac{2MkpX(t)\exp(kX(t))}{[1+\exp(kX(t))]^2}$ $X(t) = \left\{\frac{1}{k}\ln\left(\frac{2}{1-x(t)/M} - 1\right)\right\}^{\frac{1}{p}}$	M – maximum fade, k – rate, p – order

x, D: state variables
k, k_D: fade rates
p: order
M: maximum extent of fade



Machine Learning to Advance Life Models

- Kinetic feature selection for failure modes
- Bayesian Parameter Estimation
- Sensitivity analysis

Preliminary targets for BTMS (comments welcome).

Hold for data

Conclusions

The best outcome will rely on a technologically agnostic to stationary that is guided by a system level assessment.

Non-critical materials must be a foundational issue if costs are to be controlled.

Vehicle batteries will not necessary be the answer to long-term storage requirements.

Thermal storage and management will enable optimizing energy efficiency and minimizing cost in buildings applications.

Advanced lifetime models will be necessary for long lifetime outcomes.

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Thank you

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