SAND2019-13905PE

Energy Storage Research at Sandia

PRESENTED BY

Alexander Headley

U.S. Electric Grid Today

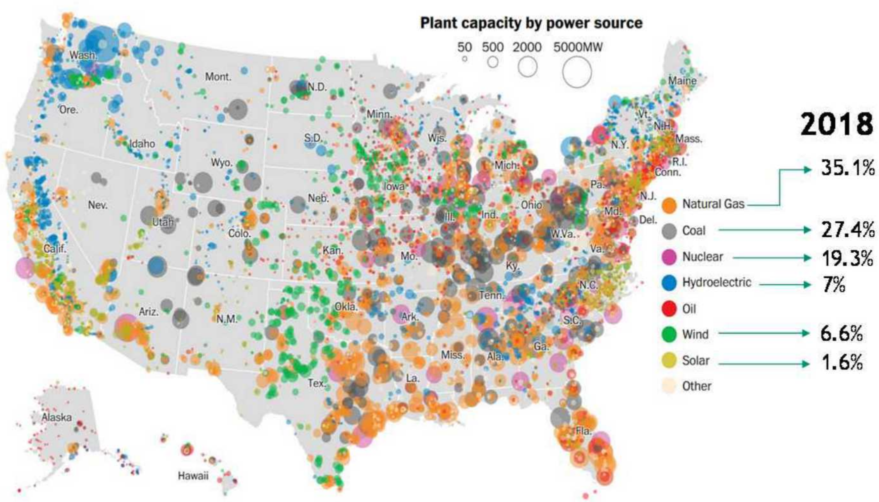
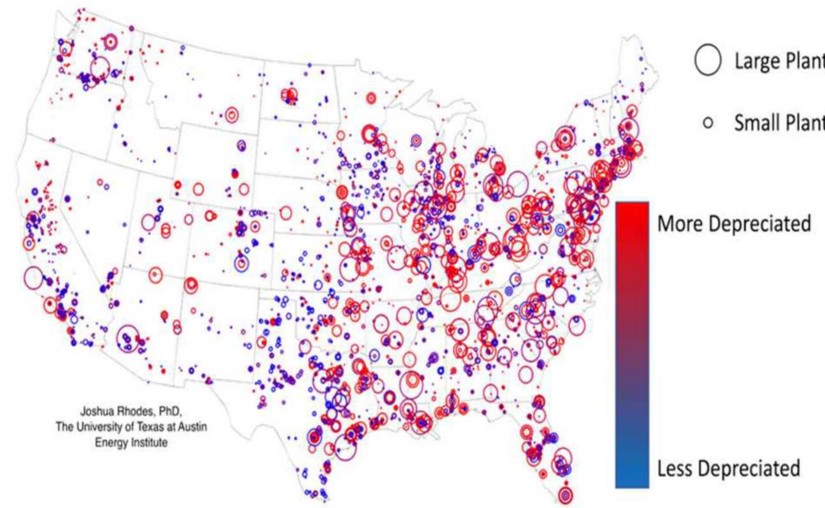


Image credit: Washington Post



Electric transmission lines

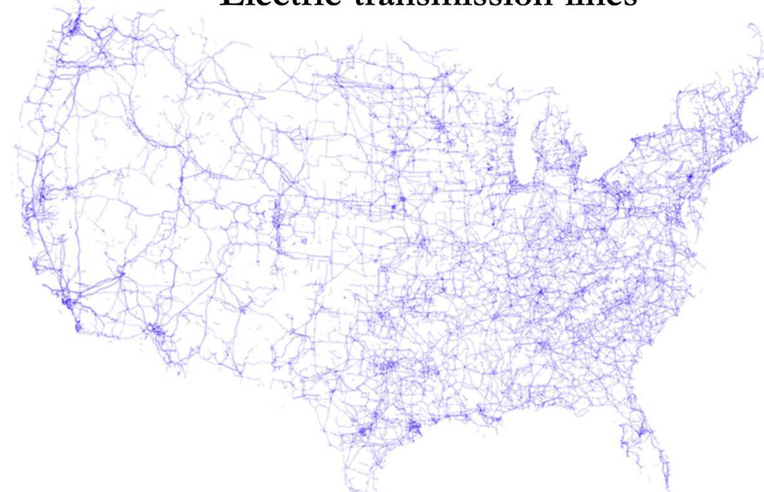
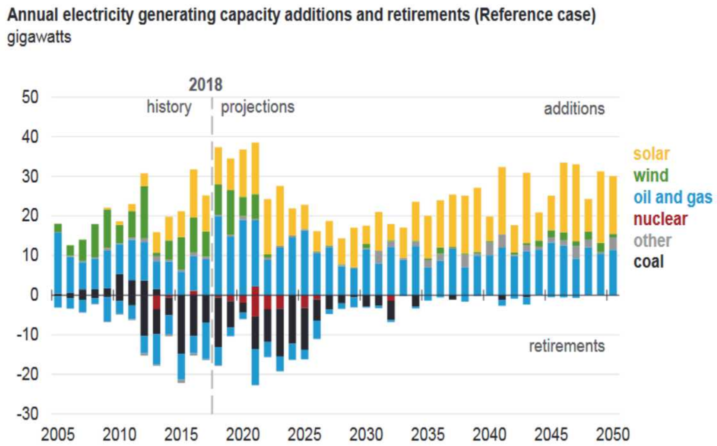


Image credit: Washington Post

- Major grid infrastructure is aging
- Accelerating retirements of coal fired power plants
- T&D congestion starting to impact deployment of renewables

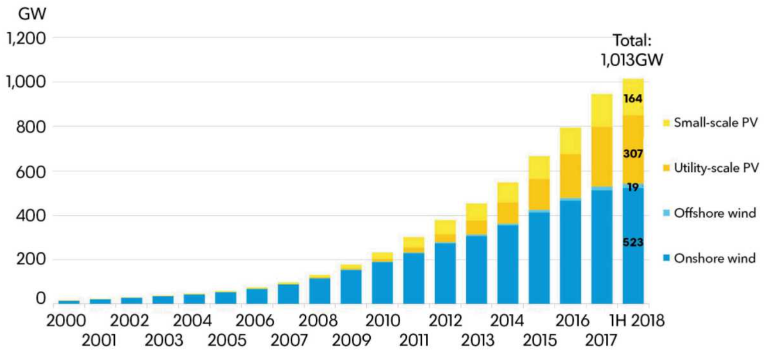
Growth of NG, Renewables, Cost Reductions

Capacity Additions and Retirements



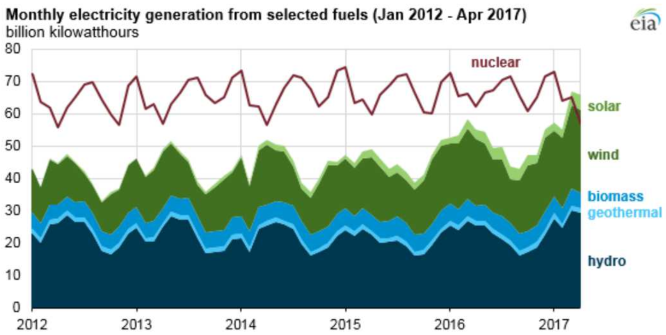
EIA Annual Energy Outlook 2019

Cumulative global solar and wind capacity (June 2018)

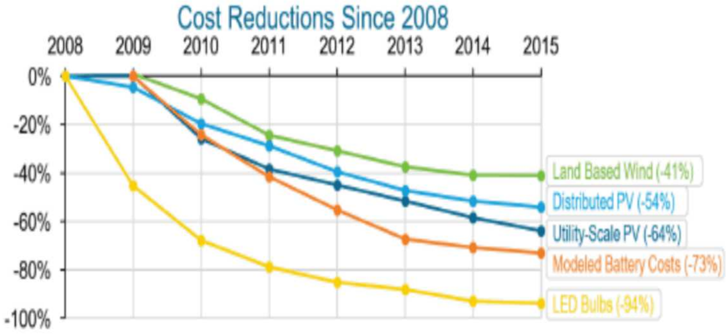


Source: Bloomberg NEF. Note: 1H 2018 figures for onshore wind are based on a conservative estimate; the true figure will be higher. BNEF typcally does not publish mid-year installation numbers.

Utility-scale Renewables Generation surpassed Nuclear Generation (April 2017)



Cost reductions primarily due to high volume manufacturing and large scale deployments



http://energy.gov/eere/downloads/revolutionnow-2016-update

Coal-fired unit retirements driven by low NG prices (EIA, 2017)

In California, solar, storage and wind capacity additions expected to exceed NG by ‘21(GTM)

Another Trend – State Policies for Clean Energy

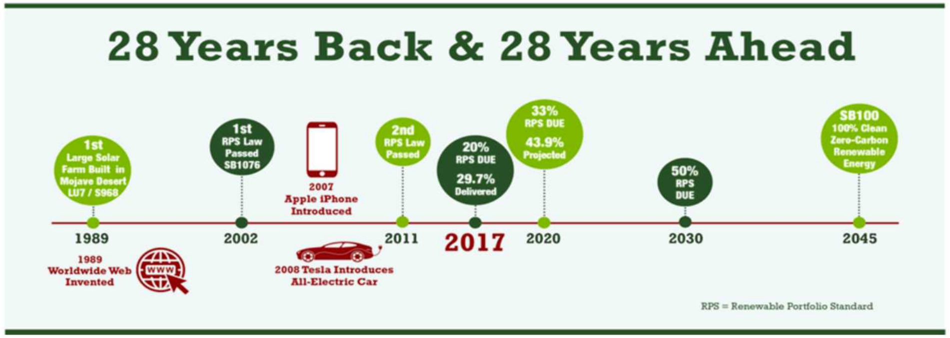
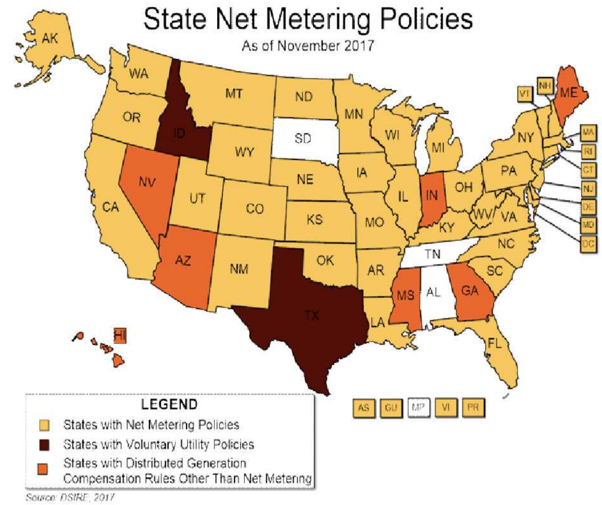
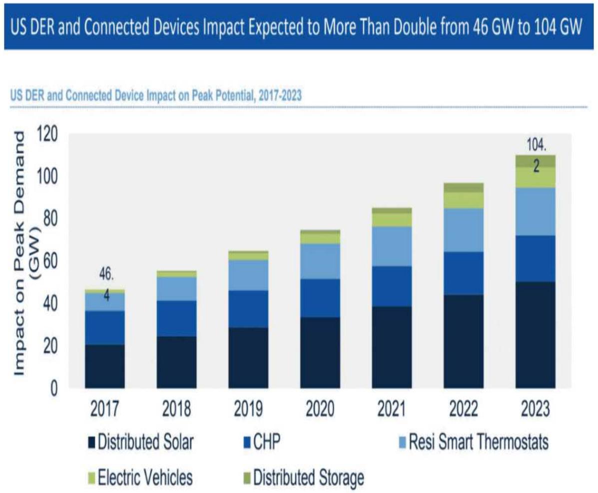


Image Source: California Senate





Source: GTM Research and US DOE

- Generation is becoming distributed
- Almost all states have Net Metering programs
- California, Hawaii, New Mexico, Washington, and Nevada legislating 100% renewable energy in the next 20-30 years.

Role of Energy Storage in the Grid

Grid resiliency and reliability

Improving power quality

Improving the efficiency of existing generation fleet

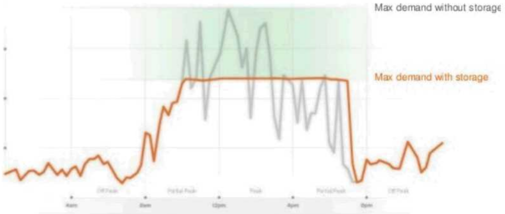
Demand management

Renewable integration

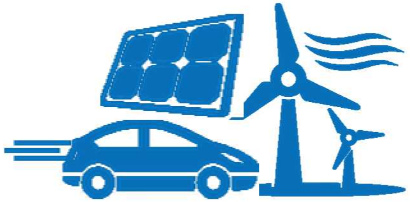
Transmission & Distribution upgrade deferral

Off-grid applications

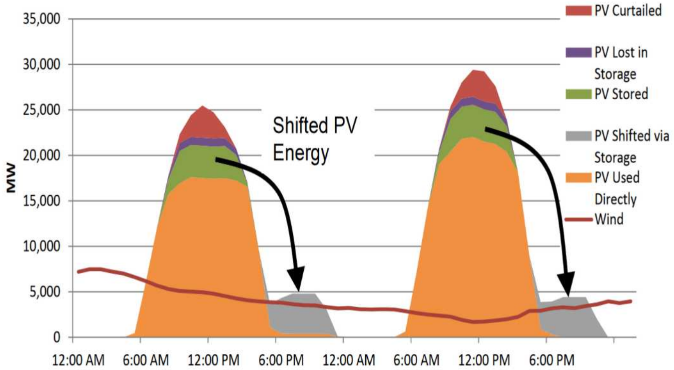
Mitigate $79B/yr in commercial losses from outages



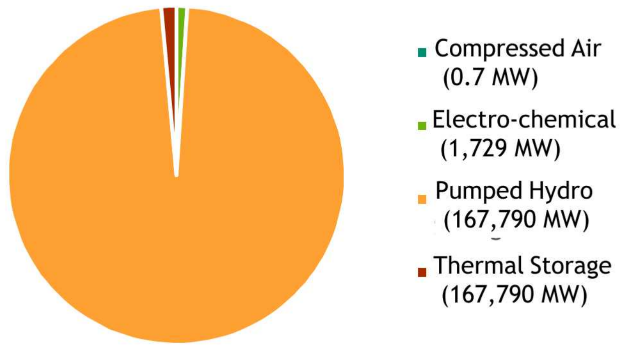
Reduce commercial and industrial electrical bills through demand charge management. 7.5 million U.S. customers are enrolled in dynamic pricing (EIA 2015)



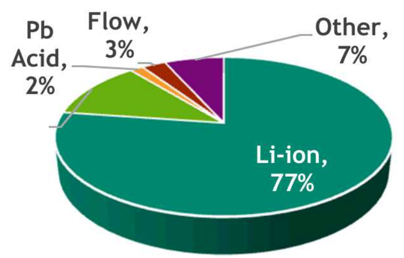
Balance the variability of 825 GW of new renewable generation while improving grid reliability and efficiency.

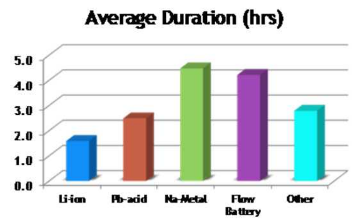


Energy Storage in the Grid Today



Global Installed Storage Capacity





US Battery Energy Storage Deployed Reached over 2 GW in 2018

Grid-Scale Energy Storage still < 0.1% of U.S. Generation Capacity

US installed energy storage capacity of 32 GW represents 15 min ride through

EV's < 1% of vehicles sold in U.S.

Technology Type	Projects	Rated Power (MW)
Electro-chemical	733	1,729
Pumped Hydro Storage	325	167,790
Thermal Storage	206	2,444
Compressed Air	1	0.660

Globally

- 1.7 GW Battery Storage, ~170 GW Pumped Hydro

U.S.

- 0.7 GW BES, 22.6 GW PHS

% of U.S. Generation Capacity

- 0.06% Battery Storage, 2.2% All Storage

Compared to the need, the scale of energy storage deployments is insignificant.
In US, we have a 1 TW grid, even 1 hr of energy storage means 1 TWh

DOE Global Energy Storage Database
www.energystorageexchange.org

Where We Focus Our Energy

Sandia is focused on developing the technologies, controls, standards, etc. to make energy storage a significant contributor to the grid of the future

Materials

Advancing battery chemistries through development and commercialization

Safety & Reliability

Testing, Analysis, Standards, Protocols

Power Electronics

Reduce installed cost and footprint

Improve control capability
Increase reliability

Regulatory Outreach

Collaborating with States and other National Labs

State Policy Analysis

Demonstration Projects

Support, Analysis, Implementation, Monitoring

Outreach

DOE ESS Website

Global Energy Storage Database

Regulatory Outreach & Education

Energy Storage Materials

Li-ion Batteries for Grid Applications

Technology – wider range than EV needs, lower costs, longer cycle life and simpler packaging

Already a dominant technology for Power Applications in the grid

Expanding range of deployments

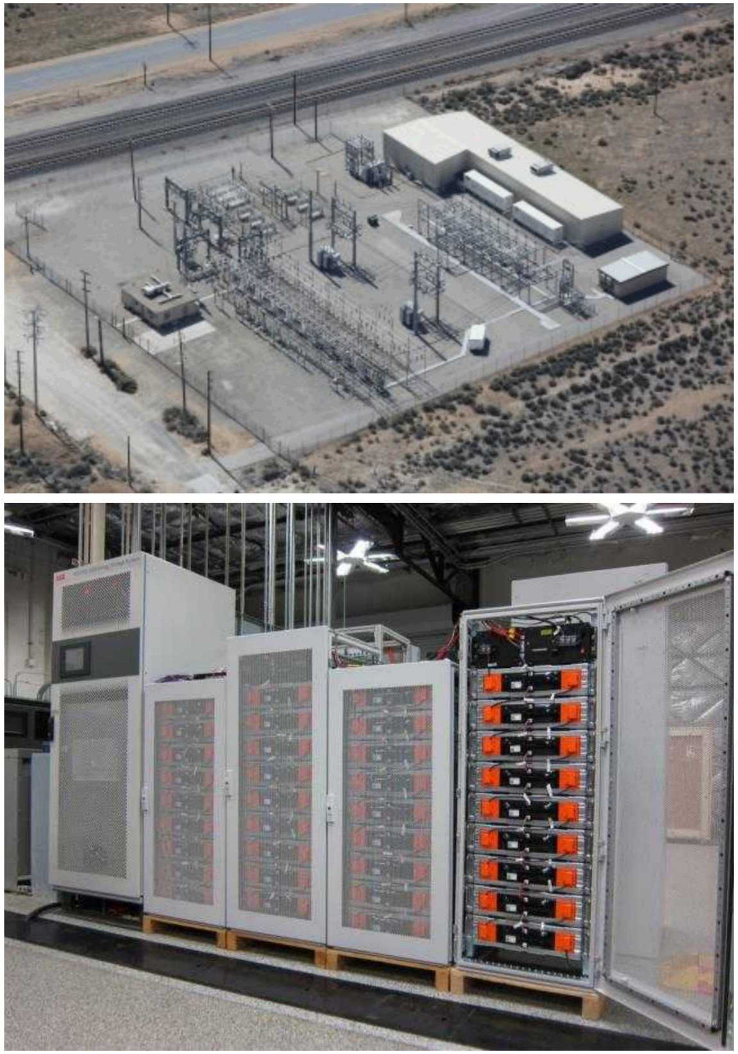
- Behind the meter, regulation, ramping products

Advantages

- High energy density
- Better cycle life than Lead - Acid
- Decreasing costs – Stationary on coattails of increasing EV.
- Ubiquitous – Range of vendors
- Fast response
- Higher efficiency

Challenges

- Intolerance to deep discharge
- Cycle life for energy applications
- Sensitive to
  - Over temperature
  - Overcharge
  - Internal pressure buildup



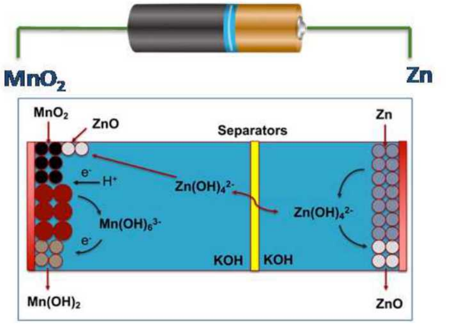
SCE Tehachapi plant, 8MW, 32MWh

Materials – BEYOND LI-ION

SODIUM BATTERIES

- New Na-battery cell testing design implemented that exhibits improved sealing, chemical compatibility, and molten reagent utilization
- Solid state separator development has yielded improved in-house NaSICON production and new alternative ion conductive ceramics and composites
- Interfacial modifications in both anode and cathode have led to drastically improved cell cycling performance, enabling >100 cycles in lab-scale prototypes

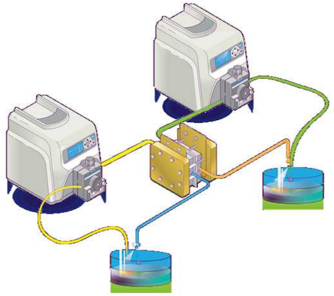
ZINC BATTERIES

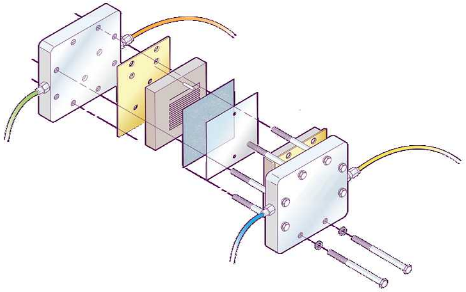


- Developed permselective polymer separators to block zincate crossover while promoting promising ionic conductivity competitive with current commercial materials
- Using Zn/Ni analogs, developed strategy in which ZnO-saturated KOH electrolyte leads to increased cycle life and more effective utilization of Zn-anodes
- Developed high voltage aqueous Zn-MnO2 rechargeable battery operating at 2.8 V without the use of expensive ion selective membranes

Materials – BEYOND LI-ION

FLOW BATTERIES



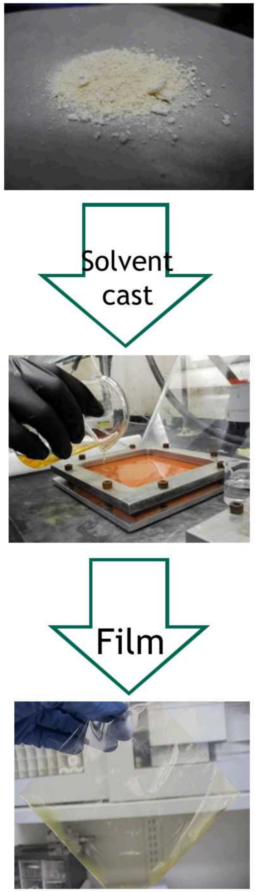


- Through testing of variable electrolyte compositions and membrane chemistries, determined new insights into the the foundation of flow batteries: the interplay between solvent, salt, and membrane
- Several university collaborations are developing new models and promising tunable redox active materials for flow batteries

MEMBRANES

Developed new process of synthesizing SNL anion exchange membrane for the specific use in flow batteries

Currently looking for commercial partners



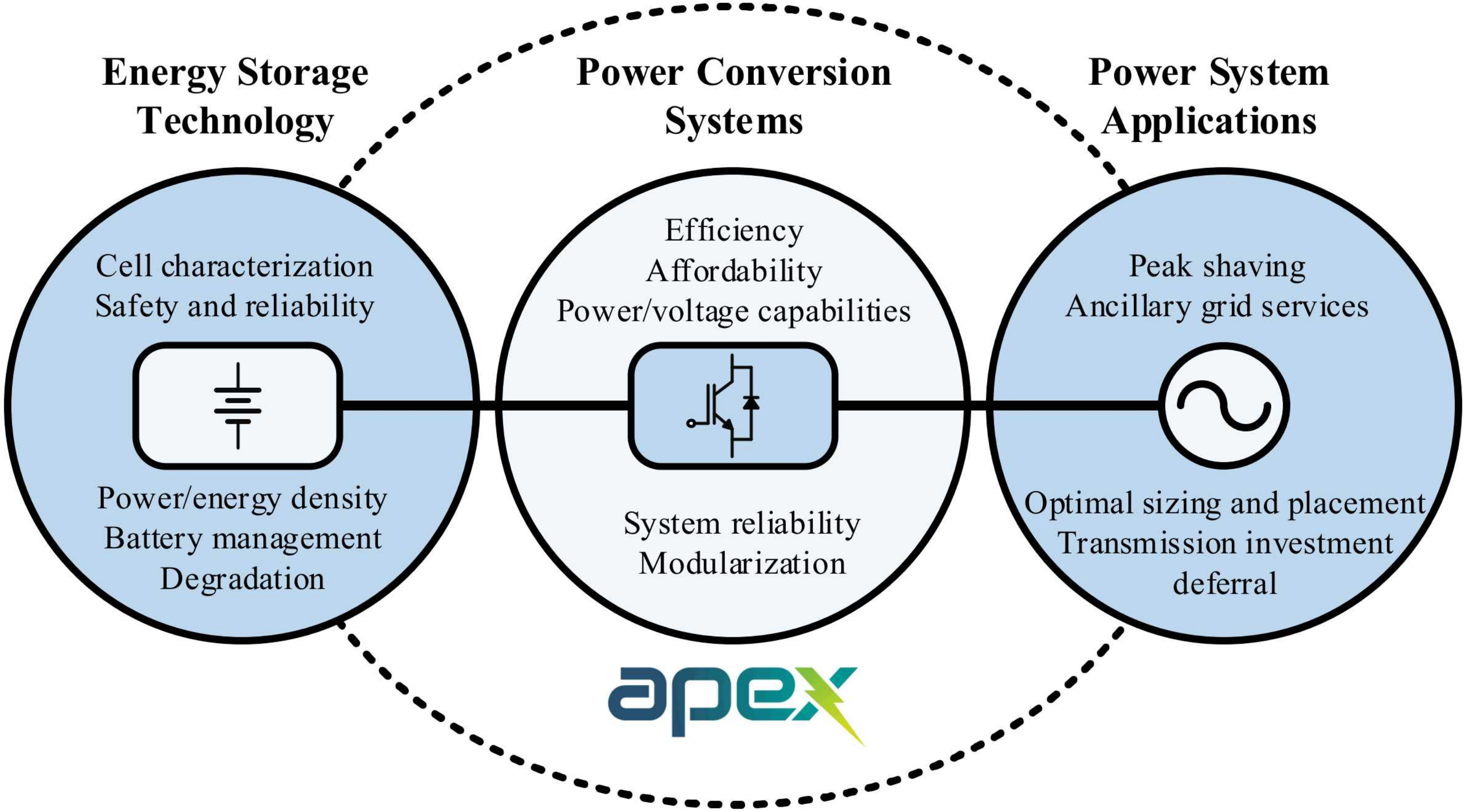
Power Electronics Area

Power Electronics OVERVIEW

The Advanced Power Electronic Conversion Systems (APEX) laboratory is:

- A new facility at Sandia dedicated to the development of next-generation power conversion systems for energy storage applications
- A rapid prototyping environment for ground-up design and integration of new hardware topologies, advanced component technologies, and intelligent control systems
- The center point of a comprehensive power electronics R&D strategy

ENERGY STORAGE R&D



APEX Lab

APEX CAPABILITIES

Simulate
Real-time simulation of components, converters, and systems
Ansys Maxwell, Matlab/Simulink, PLECS, PSIM, Opal-RT FPGAsim

Design
Electrical and mechanical CAD tools for PCB design and converter assembly
Autodesk Eagle, Solidworks, Solidworks PCB, ORCAD

Construct
Automated assembly equipment for in-house production of converter prototypes
Manncorp MC400 Pick and Place Machine, MC301 Reflow Oven

Control
Reconfigurable digital control platforms for development of new control strategies
Code Composer Studio, TI C2000 DSPs, Vivado, Xilinx FPGAs and SoCs

Analyze
Fully bidirectional hardware-in-the-loop testbed for assessment of converter performance in practical application scenarios
30kW Grid Simulator, DC Sources up to 950V/±40A, Comemso 144-Ch Cell Simulator

Stress
Fault-tolerant source equipment and protective enclosure for destructive testing
Custom polycarbonate enclosure, Opal-RT master system controller

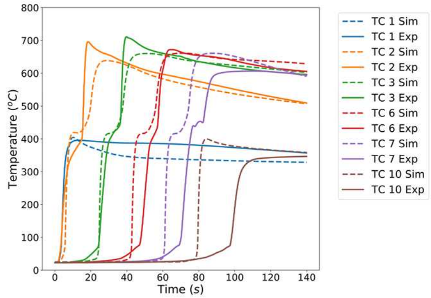
Systems Safety & Reliability

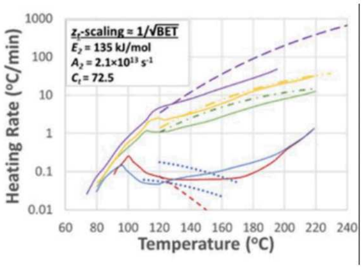
Safety & Reliability

Modeling

Spearheading advancements in multi-scale modeling of Li-ion battery failure, including development of:

Models for thermal runaway propagation in pouch cells



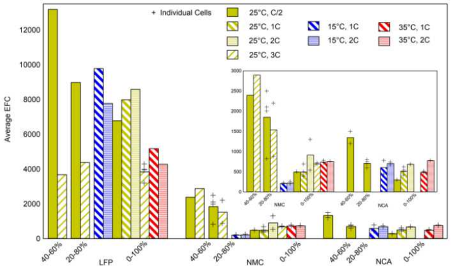


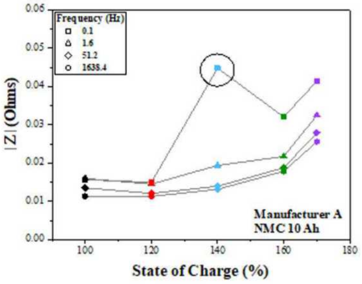
Comprehensive models of lithiated graphite and metal oxide cathode decomposition

Experimental

Advancing quantification of battery degradation and failure at the cell and materials level, including:

Completed multi-year head-to-head comparison of cycling, materials stability, and whole cell thermal runaway of popular commercial Li-ion cells





Identified universal degradation markers for NMC cells, providing early warning of failure

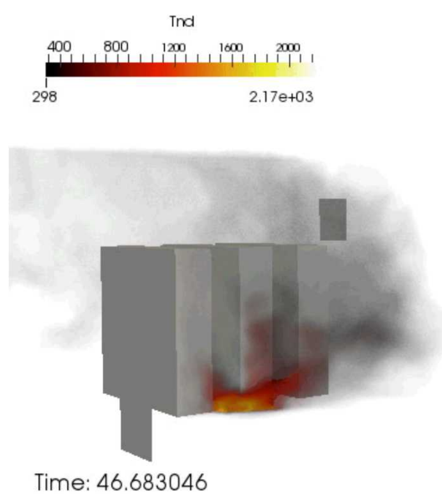
Approaches to engineered safety

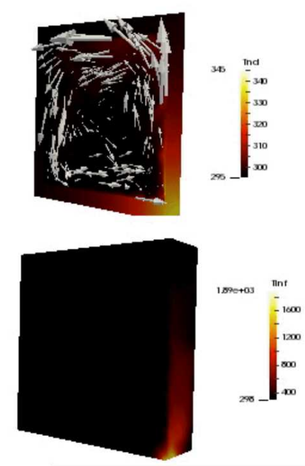
The current approach is to test our way into safety

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

Supplement testing with predictions of challenging scenarios and optimization of mitigation.

- Develop multi-physics models to predict failure mechanisms and identify mitigation strategies.
- Build capabilities with small/medium scale measurements.
- Still requires some testing and validation.





Cascading failure testing with passive mitigation

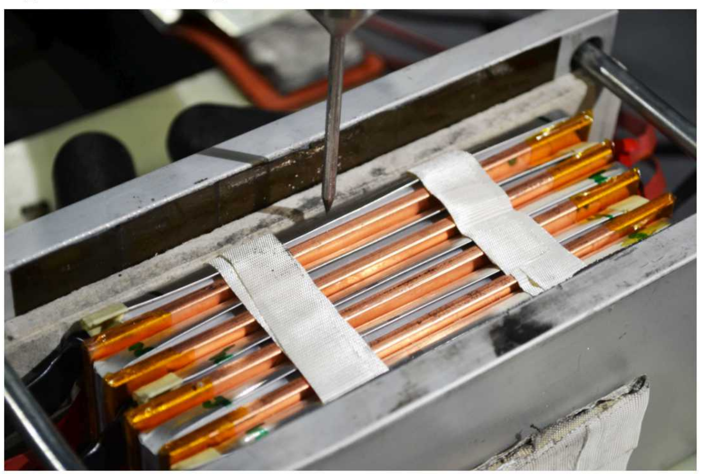
$LiCoO_2$ 3Ah pouch cells

5 closely packed cells with/without aluminum or copper spacer plates

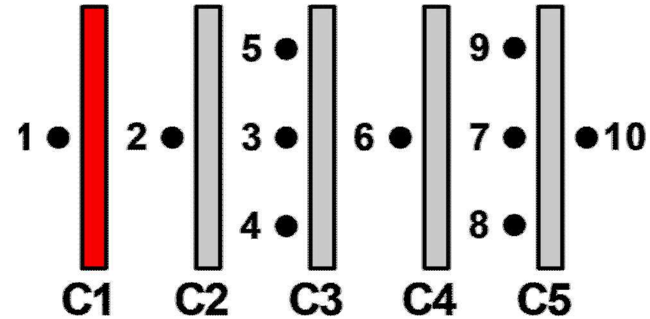
- Spacer thicknesses between 1/32" and 1/8"
- State of charge (SOC) between 50% and 100%

Failure initiated by a mechanical nail penetration in the outer cell (cell 1)

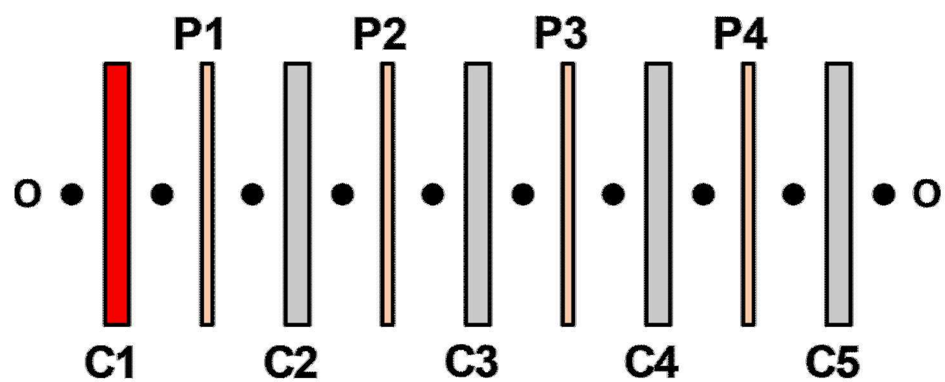
Thermocouples (TC) between cells and spacers (if present)



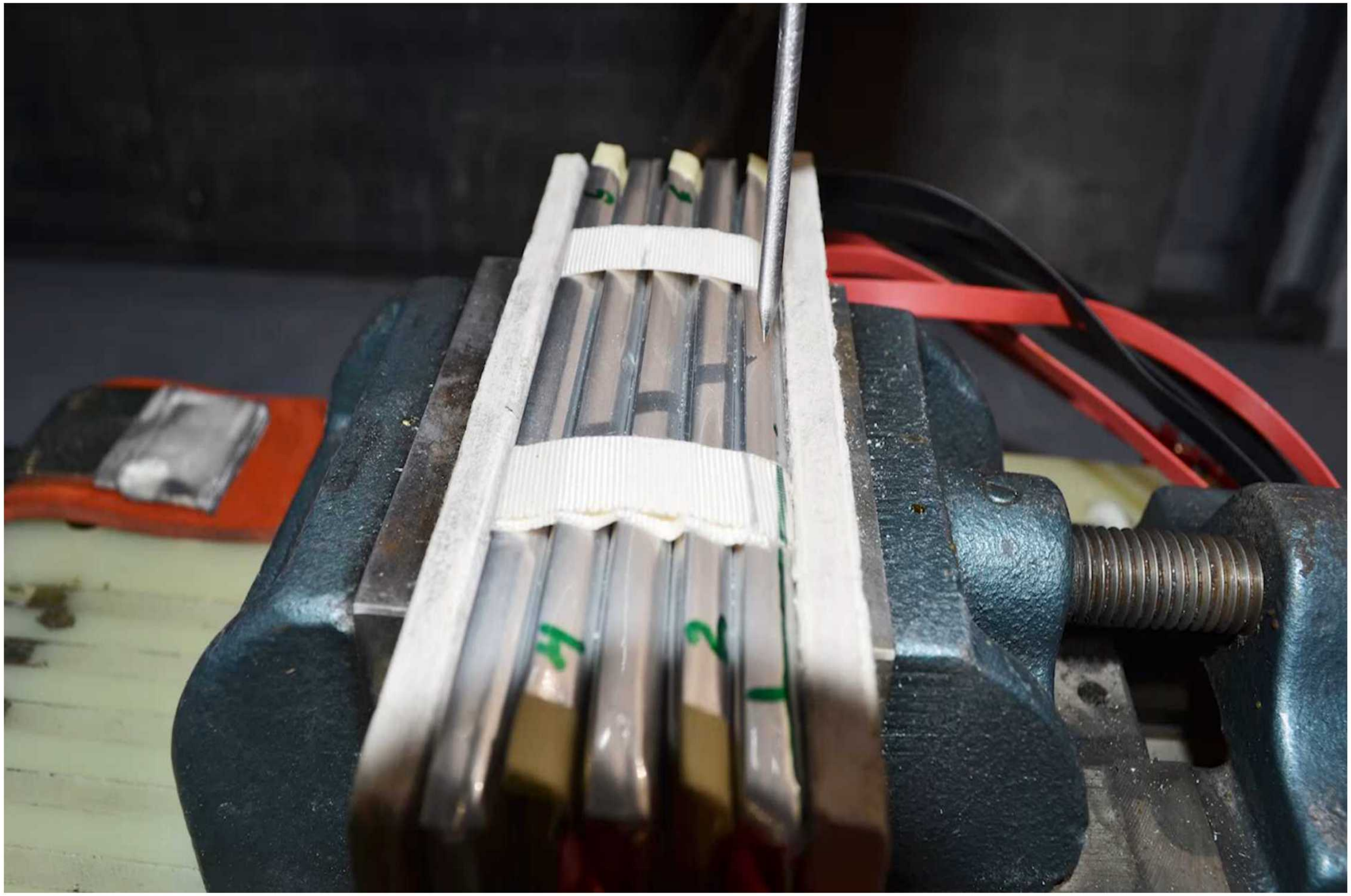
Thermocouple Locations



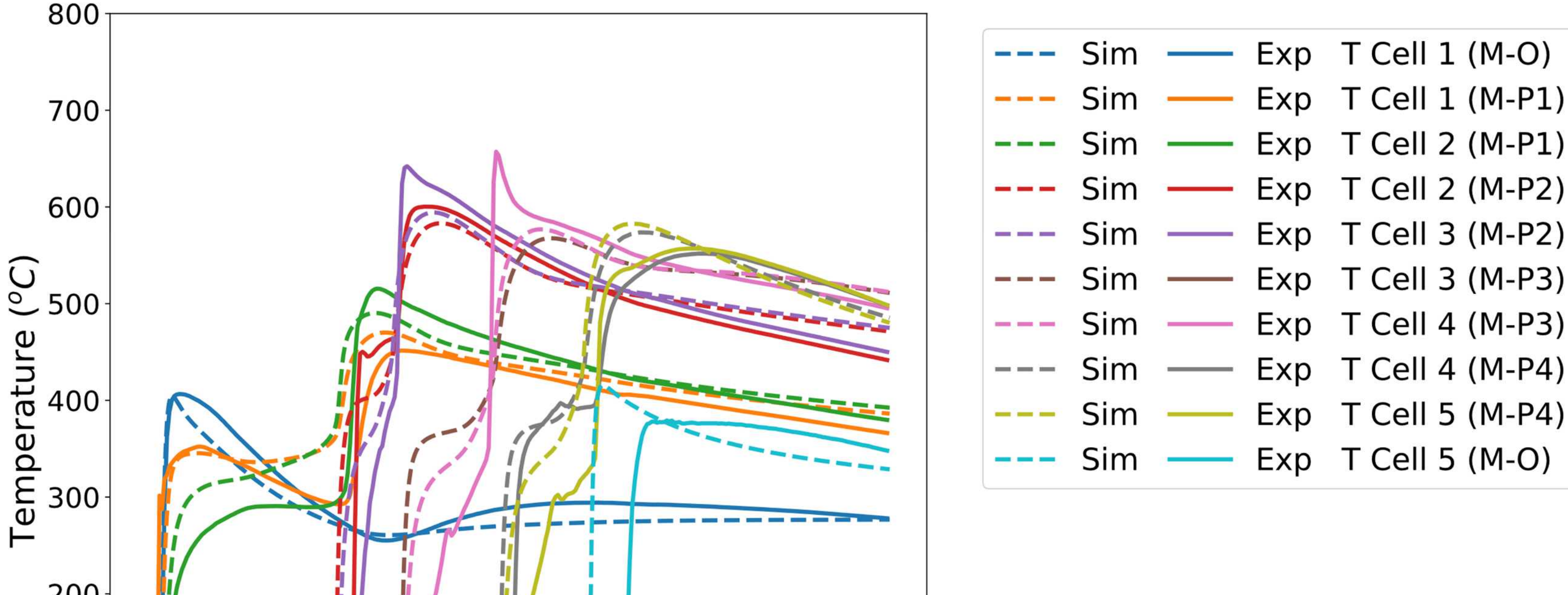
Thermocouple Locations with spacer plates

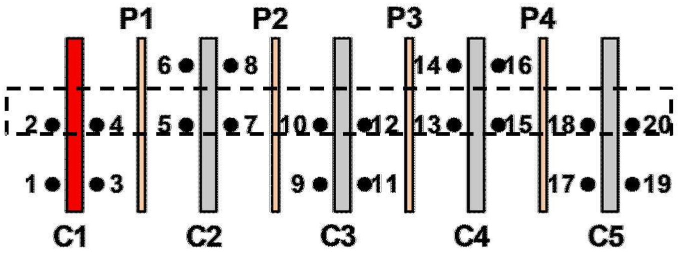


Cascading failure testing



Simulation results: 100% SOC, 1/32" aluminum spacers





- Temperature difference in TCs on either side of the plates under-predicted
- Cell crossing speed still over-predicted

Demonstrations Projects

Energy Storage Demonstration Projects

Work with Utility, Industrial, State and International entities

Provide third party independent analysis

Support the development and implementation of grid-tied ES projects

- RFI/RFPs development
- Design and Procurement Support
- Application/Economic analysis
- Commissioning Plan Development

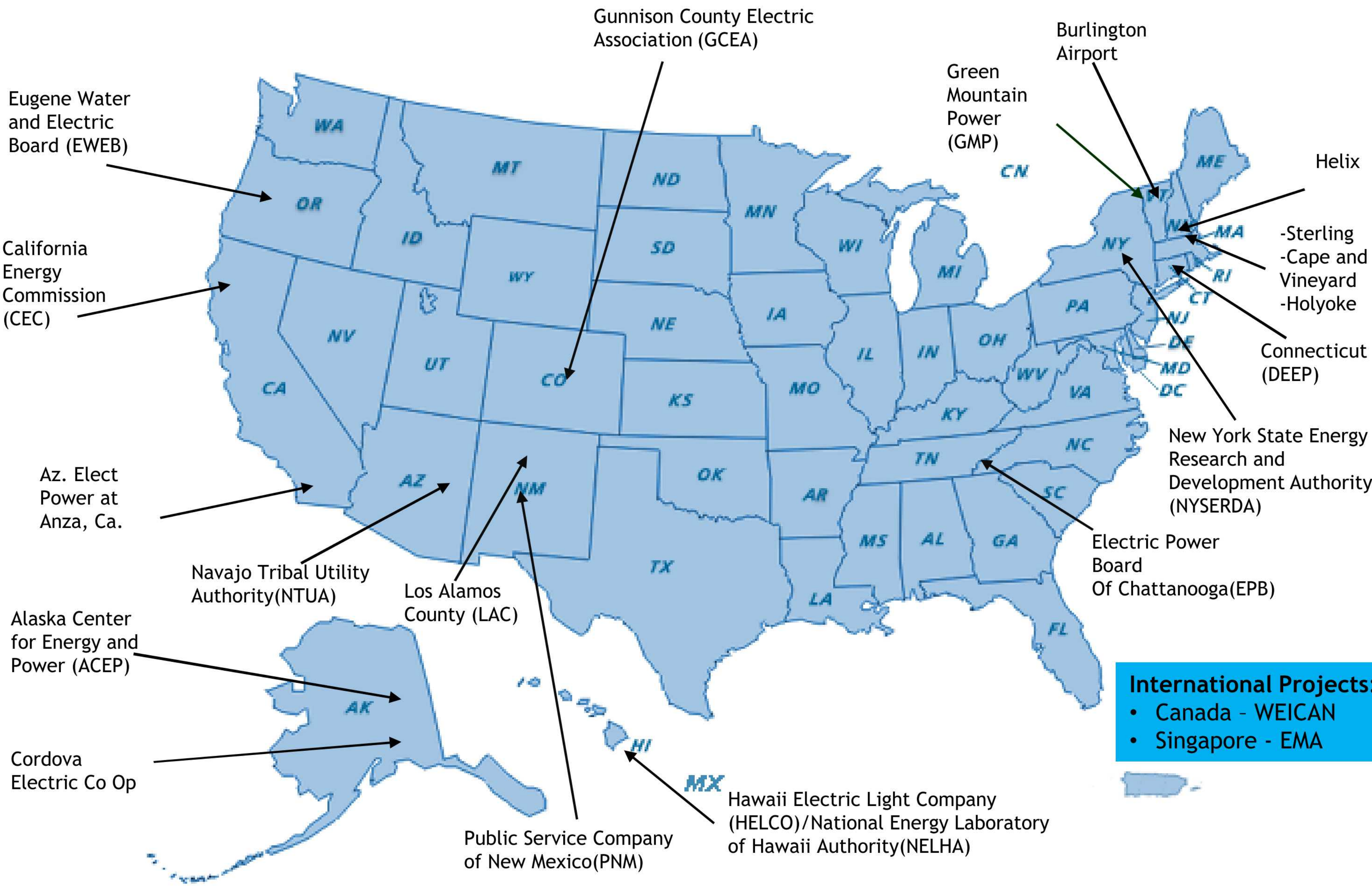
Monitor and analyze operational ES Projects

- Application validation
- System optimization
- Operational performance analysis

Develop public information programs

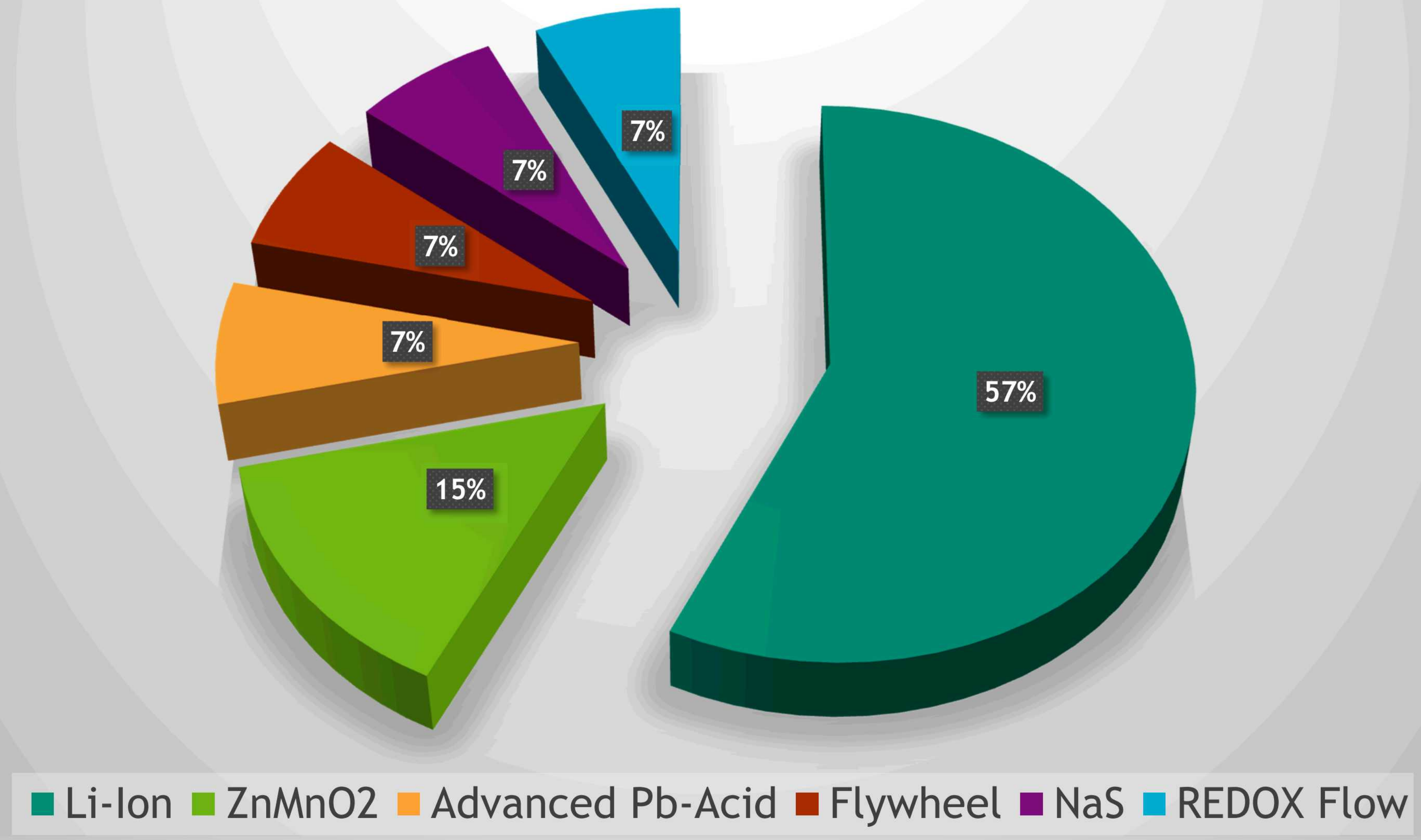
Inform the Public and encourage investment.

Energy Storage Demonstration Projects



International Projects:
- Canada – WEICAN
- Singapore - EMA

Energy Storage Project Technologies

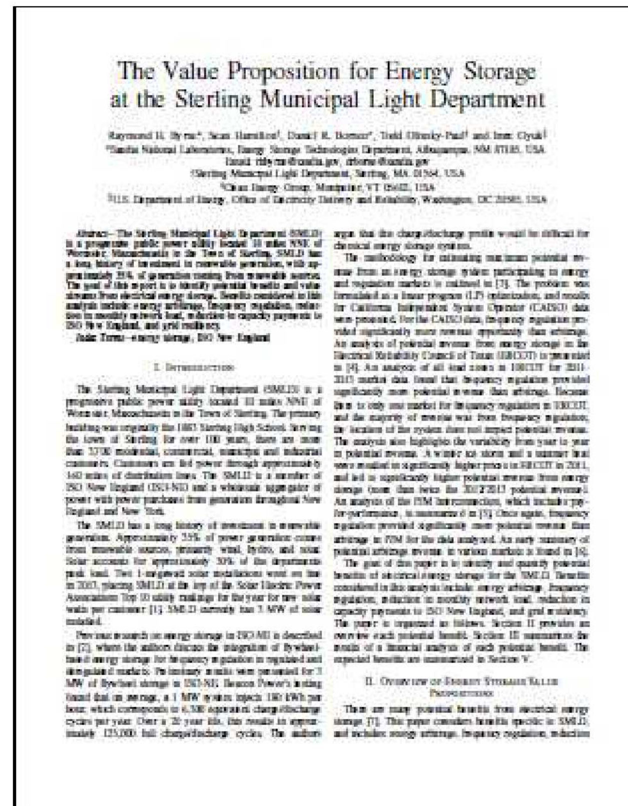


Example Deployment Project: Sterling Municipal Light Department

- Conducted an economics analysis showing ~6 year payback for battery system (2.5 years with grants)
- Installed a 2 MW/ 3.9 MWh Li-ion battery storage system in Sterling Massachusetts

Along with the existing PV array, ES can island from grid and provide 12 days of backup power to the Sterling police station

Demand reduction application saves the ratepayers ~$400,00 per year by decreasing the costs associated with capacity and transmission charges


The Value Proposition for Energy Storage at the Sterling Municipal Light Department

Example Demonstration Project – Santa Fe Community College

100kW / 170kWh system to provide power for greenhouse operations

- PV resources already online

Possibility for useful stack thermal measurements

- Module to module temperature differences
- Effectiveness of HVAC unit
- Battery cavity modeling

SFCC considering larger system to turn the campus into a self-sustaining microgrid

Battery system commissioning later this month

Demonstration Areas (Data Collection)

Data Collection greater than 1 year

- Green Mountain Power (Vermont)
  - Dynapower, Li-Ion and Advanced Lead Acid, 4MW / 3.4MWh
- Sterling Municipal Lighting Department (Massachusetts)
  - NEC, Li-Ion, 2MW / 3MWh

Data Collection less than a year or coming online

- Cordova Electric Cooperative (Alaska)
  - SAFT, Li-Ion, 1MW / 1MWh
- Eugene Water and Electric Board (Oregon)
  - NEC, Li-Ion, 500kW / 1000kWh
- Sandia (New Mexico)
  - UEP, $ZnMnO_2$, 500W / 1500Wh
  - UET, Vanadium Redox Flow, 250kW / 1000kWh
- Santa Fe Community College (New Mexico)
  - NEC, Li-Ion, 100kW / 170kWh
- Energy Market Authority (Singapore)
  - Wartsila, Li-Ion, 2.4MW / 2.4MWh

Demonstrations Projects Looking Forward

A lot of work with Li-ion technologies going now

- Coincident peak reductions
- BTM charge reductions
  - Time-of Use & Peak demand
- Typically 2-4 hours of storage
- Becoming more common and well known in the industry

More focus on the *next* technologies and applications

- Alternate technologies
  - Flow batteries, Zn-batteries, Sodium batteries, etc.
- High renewable penetration → long duration needs and large installations
  - Major RPS updates
  - Microgrids
- Peaker plant replacements
- "Research" qualities
  - How do controls/communications have to change?
  - What is the readiness level?
  - Safety/thermal concerns?

Energy Storage Analytics

Energy Storage Analytics

Cost-benefit Analysis	Impact Analysis	Optimal Design	Optimal Control

Enhancing the security of transmission systems

- Transmission operations and planning with energy storage

Integration of distributed energy resources (DERs)

- Power flow management under high DER penetration
- Power quality enhancement using distributed storage

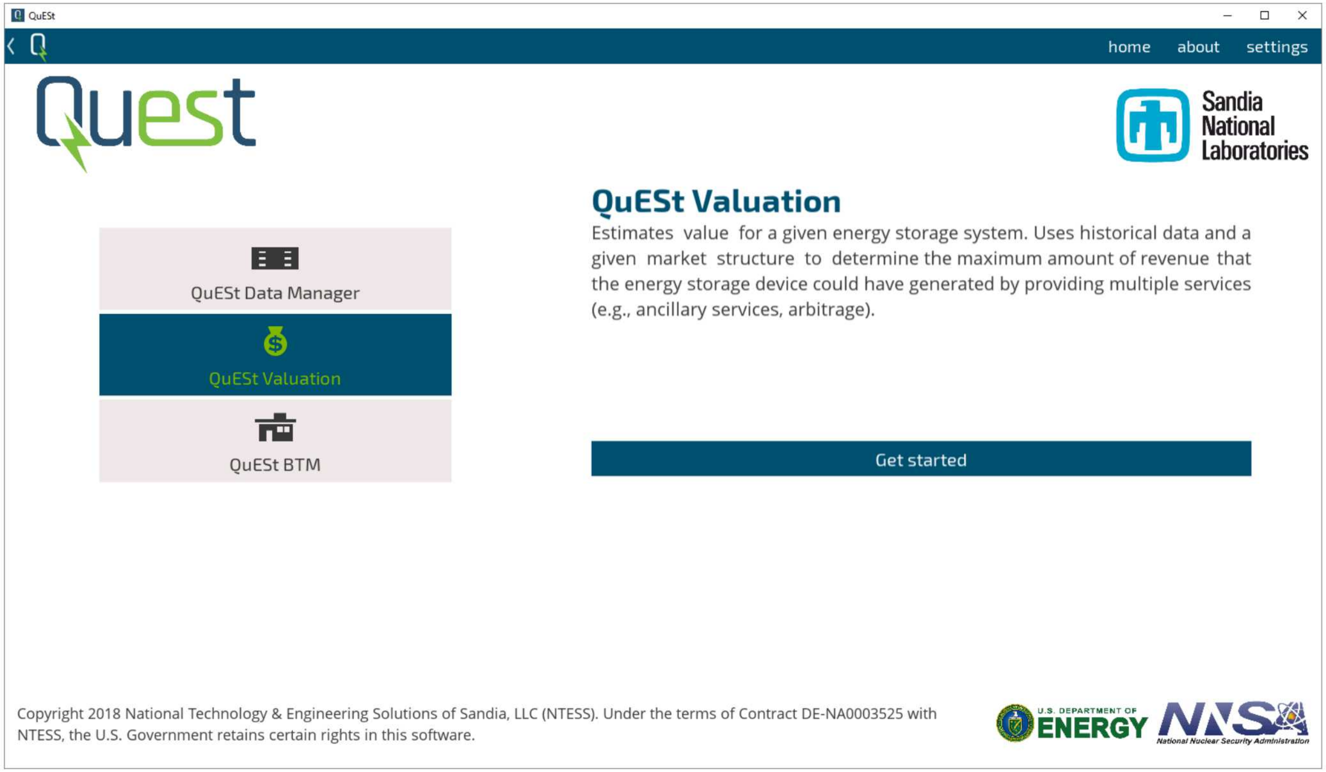
Enhancing grid reliability and resiliency

- Reducing the risk of long outages
- Minimizing damages to the grid, Black start capabilities, islanding

Maximizing potential revenue of grid energy storage:

- Analysis to support storage deployment in different markets
- Identification and valuation of new grid services

What is it?



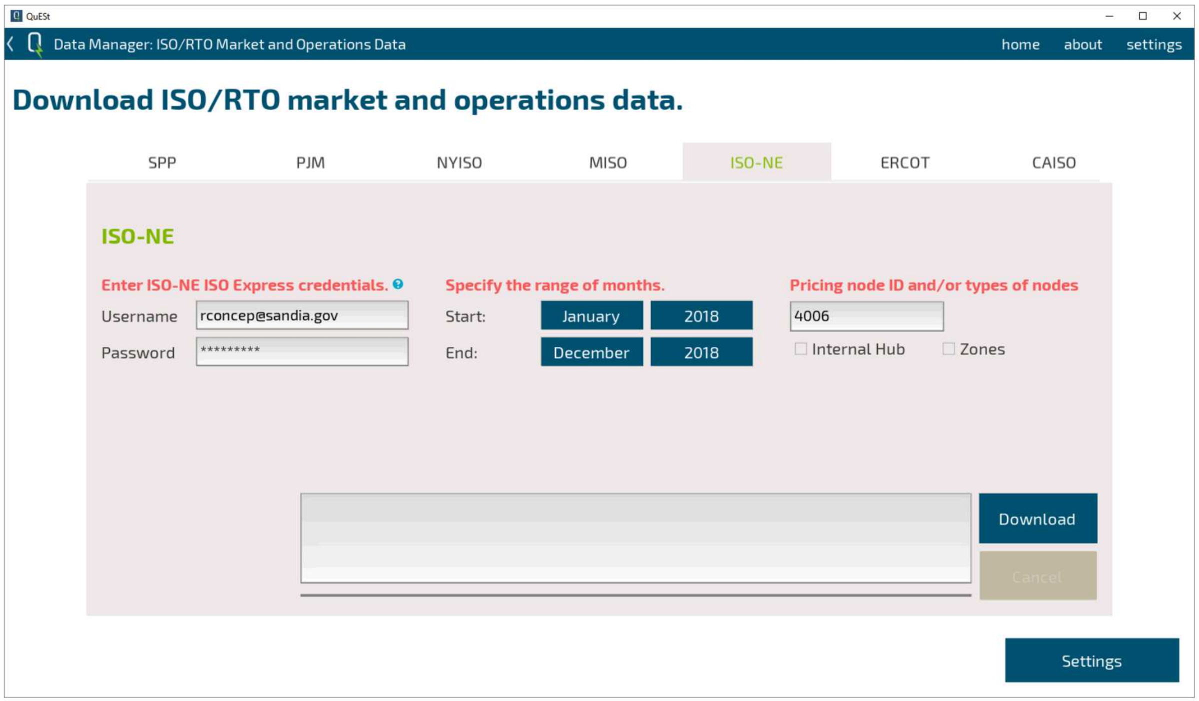
- Open source, Python-based energy storage analysis software application suite
- Developed as a graphical user interface (GUI) for the optimization modeling capabilities of Sandia's energy storage analytics group
- Version 1.0 publicly released in September 2018
- Version 1.1 available on GitHub; Version 1.2 coming soon
  - github.com/rconcep/snl-quest or sandia.gov/ess

Why QuESt?

- For energy storage project stakeholders
  - Accessible and easy-to-use software tool for energy storage valuation and related applications
- For engineers/developers
  - Open source software project
  - GUI design, application design, Pyomo optimization modeling
  - Pyomo models and other optimization code can be adjusted to fit specific needs
- It's free
  - Written in Python; no software licenses required
- Current application list
  - QuESt Data Manager – Manages acquisition of ISO market data, US utility rate data, commercial and residential load profiles, etc.
  - QuESt Valuation – Estimate potential revenue generated by energy storage systems providing multiple services in the electricity markets of ISOs/RTOs.
  - QuESt BTM* - Estimate the cost savings for time-of-use/net energy metering customers using behind-the-meter energy storage systems.
  - Continuing to add functionality to cover more cases

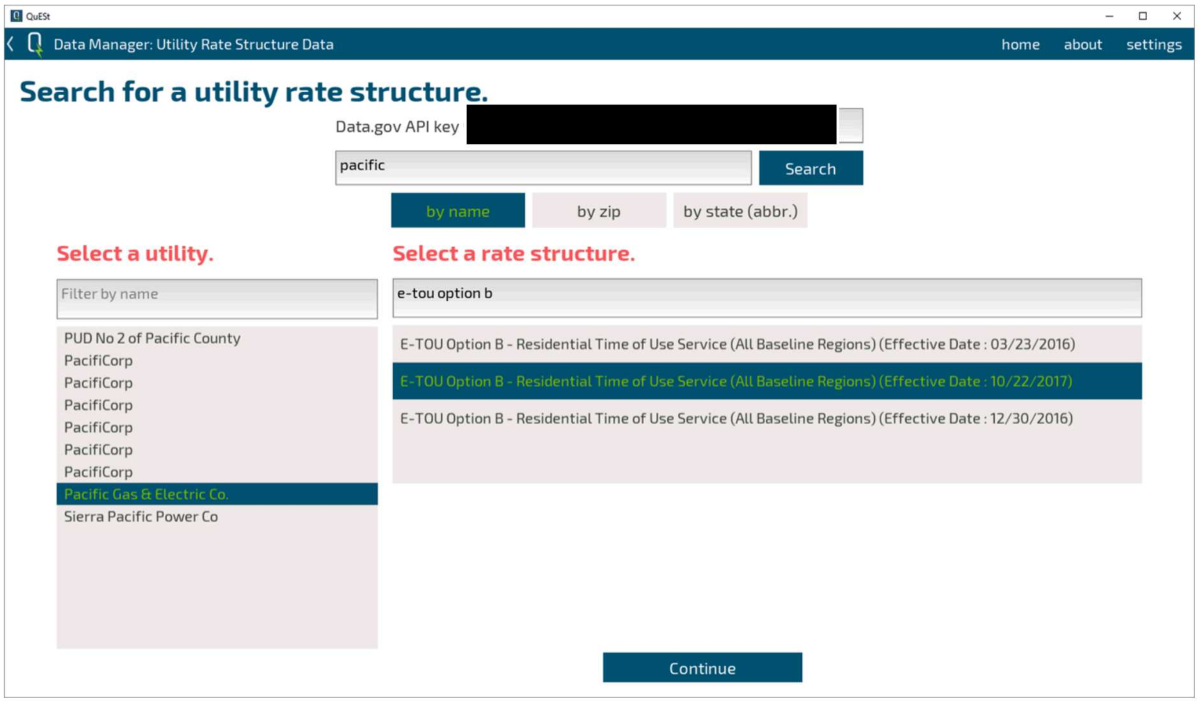
* For v1.2 release

QuESt Data Manager



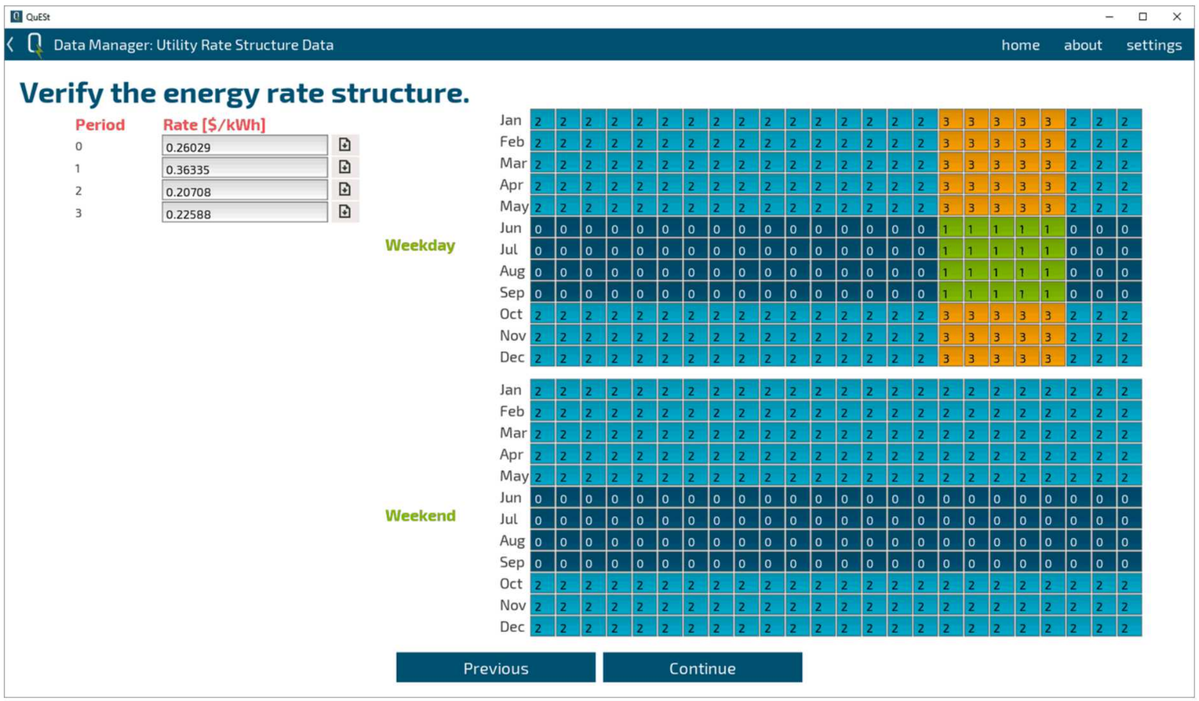
- LMPs, frequency regulation performance/capacity clearing prices, etc. posted by ISOs/RTOs
- Use operator-provided APIs, some requiring a short registration for an API key
  - ISONE, PJM
- Use web crawling libraries to parse marketplace data portals to find data files

QuESt Data Manager



- OpenEI.org, maintained by NREL, hosts a database for U.S. utility rates
- Time-of-use energy rate schedules
- Peak demand and flat demand rate schedules

QuESt Data Manager



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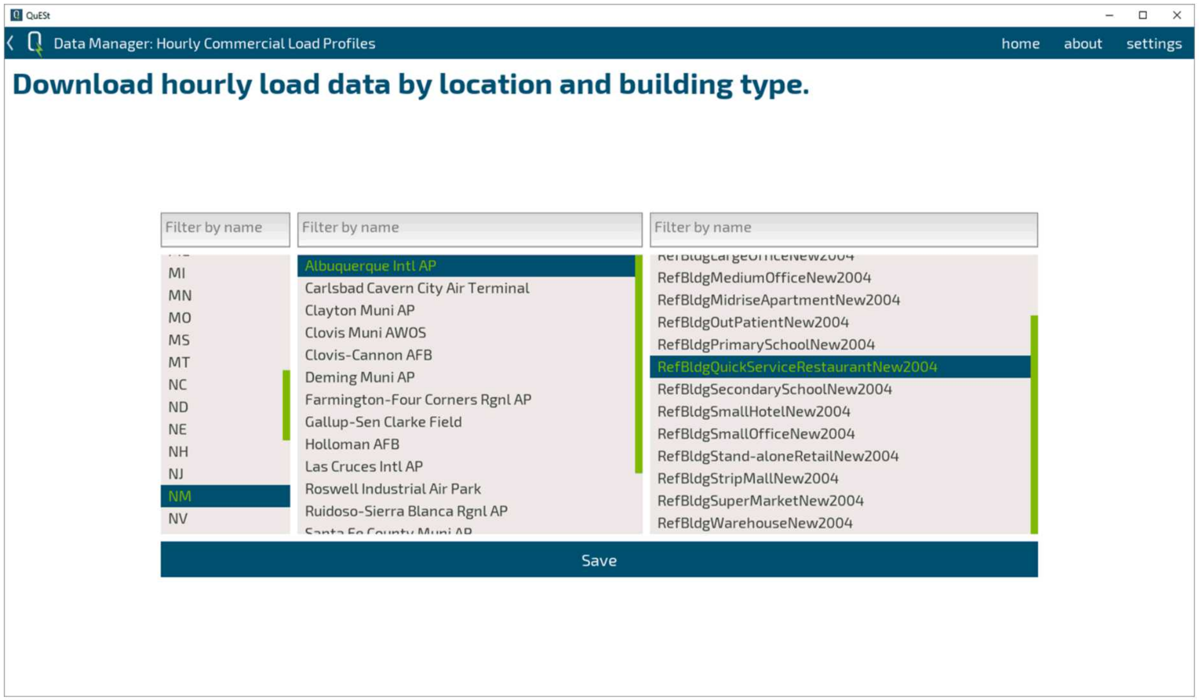
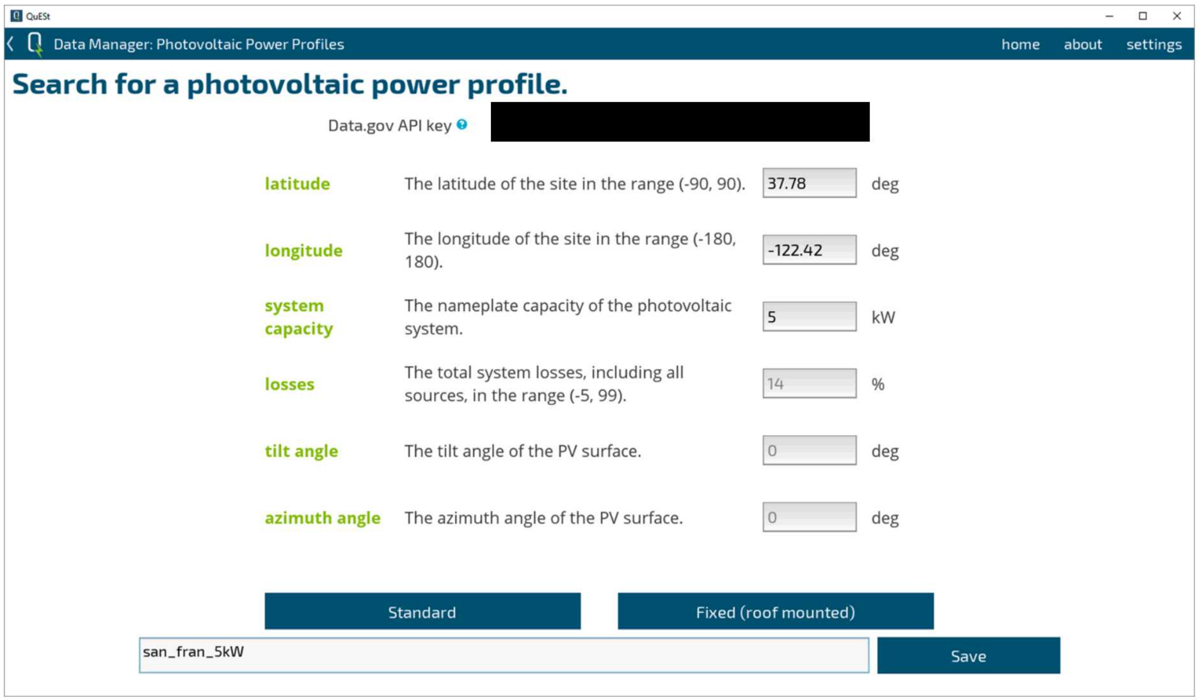


- OpenEI.org also hosts simulated hourly load profiles for TMY3 (typical meteorological year)
  - Residential (base, low, high)
  - Commercial (16 reference building types by DOE)

https://openei.org/datasets/dataset/commercial-and-residential-hourly-load-profiles-for-all-tmy3-locations-in-the-united-states

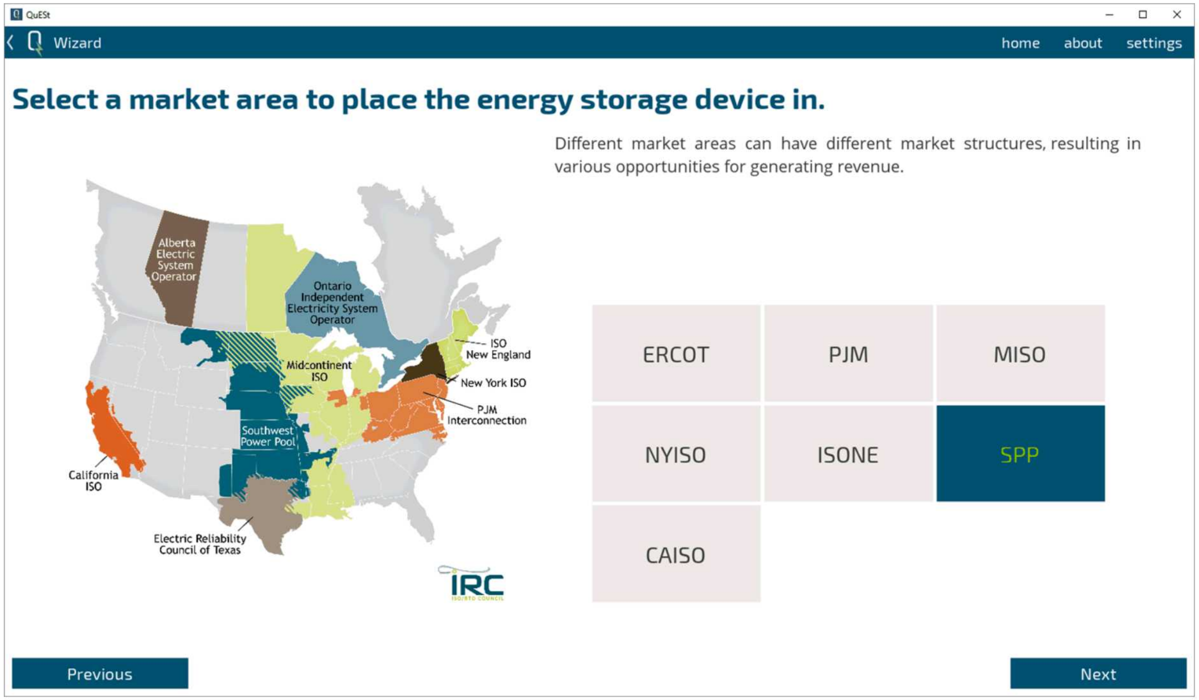
QuESt Data Manager



- PVWatts by NREL
  - Uses data from the National Solar Radiation Database and a solar panel system model to simulate hourly power output

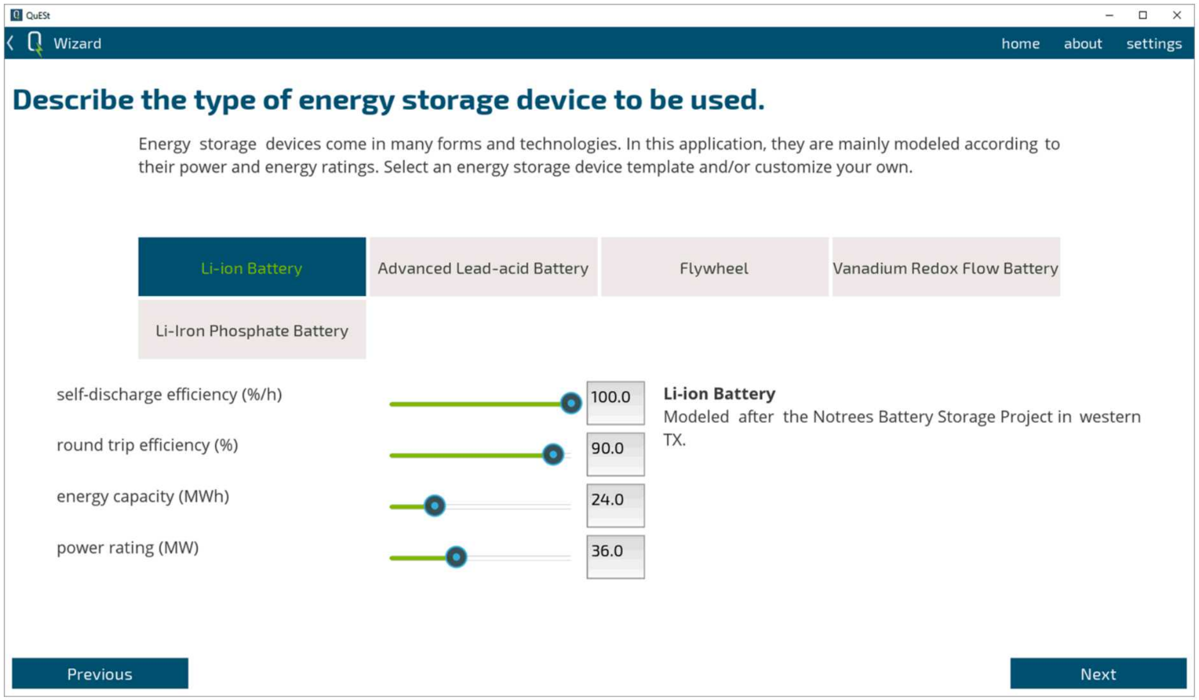
https://pvwatts.nrel.gov/version_6.php

QuESt Valuation



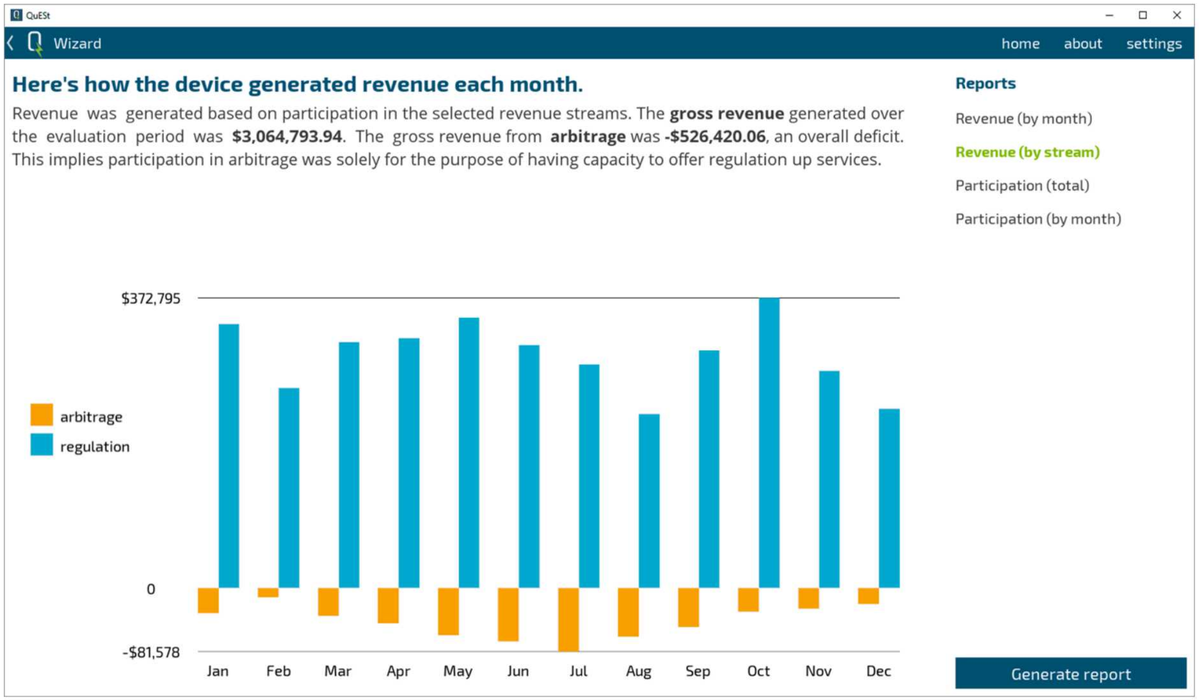
- Market area
- Arbitrage and Frequency Regulation streams
- Historical dataset to study
- Energy storage model parameters

QuESt Valuation



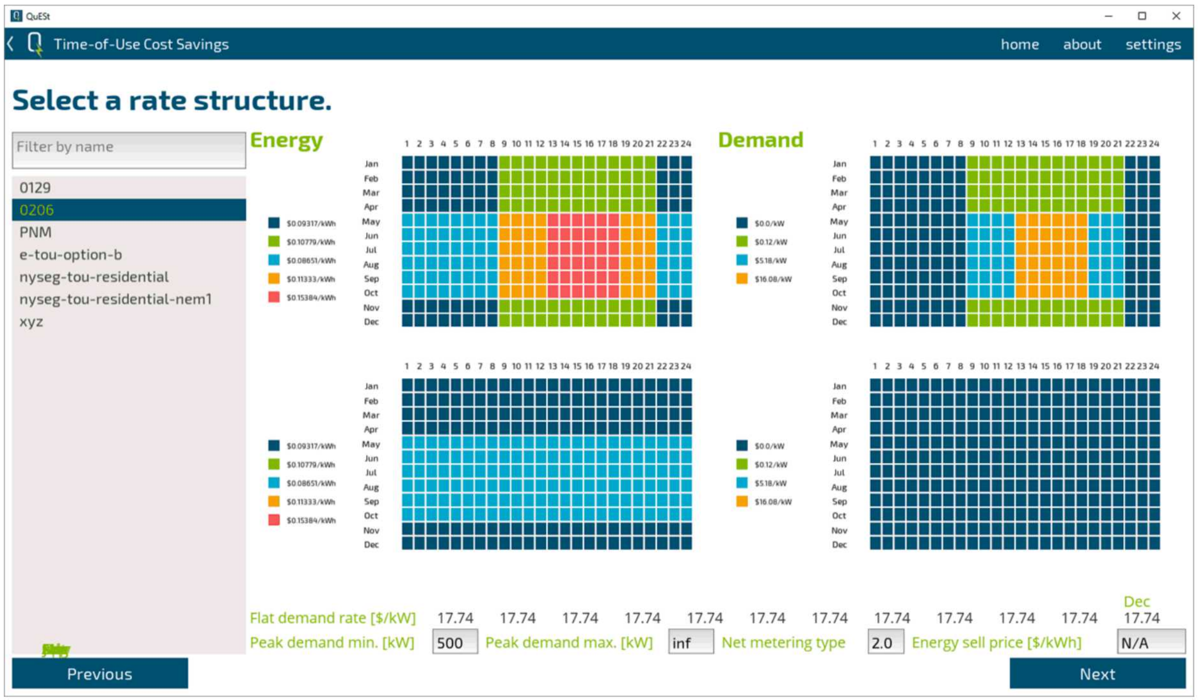
- Market area
- Revenue streams
- Historical dataset to study
- Energy storage model parameters

QuESt Valuation



- Revenue by month
- Revenue by revenue stream
- Frequency of participation in each available revenue stream

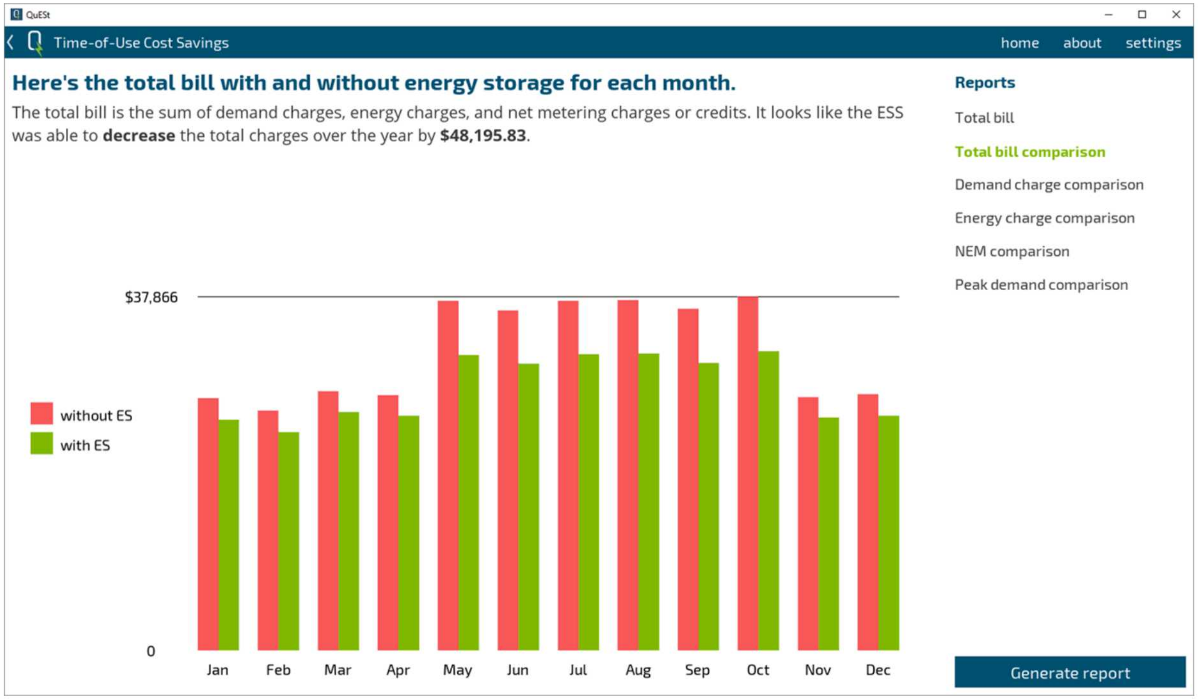
QuESt BTM*



- Utility rate structure for time-of-use energy rate schedules, demand rate schedules, net metering, etc.
- Load profile based on building type
- PV profile if solar + storage configuration
- Energy storage system parameters

*For v1.2 release; content is under development and subject to change.

QuESt BTM*



- Compare monthly bill with and without energy storage
- Peak demand reduction to decrease demand charges
- Time-shifting to reduce time-of-use energy charges
- Net metering credits

*For v1.2 release; content is under development and subject to change.

Example Analysis – NELHA Research Campus

NELHA campus loads are changing significantly

- ~200kW total PV generation
- ~180kW peak load currently
- No net metering

A new hydrogen production facility will fuel three fuel cell buses

- 250kW facility
- Flexible operation 10-100%

How to minimize the impact of the facility and best use PV?

- Peak demand charges
- Time-of-use options
- Power factor adjustments
- Would energy storage help?

Example Analysis – NELHA Research Campus

Minimize energy charges with optimal dispatch of energy storage

Scheduling of hydrogen production facility also an option

Working with HNEI to model facility operations

Research Campus Load and Costs

$$\min_{P_C, P_D, P_{H2}} \quad P_{peak} \cdot C_{Dem} + \sum_{t=1}^{T} P_{FG,t} \cdot \frac{\Delta t}{60} \cdot \left(C_{E,t} + C_{fixed,kWh} \right) + \frac{\sum_{t=1}^{T} S_{t+} + S_{t-}}{K}$$

$$\textit{subject to} \quad SOC_t = SOC_{t-l} + \frac{\Delta t}{60} \left(P_{C,t-1} \eta_{RT} - P_{D,t-1} \right)$$

$$P_{FG,t} = P_{Dem,t} + P_{H_2,t} + P_{C,t} - P_{D,t} - P_{sol,t} + P_{curt,t}$$

Hydrogen Production Model

$$SOE_{H_2,t} = SOE_{H_2,t-1} + \frac{\Delta t}{60} P_{H_2,t} - D_{H_2,t}$$

$$0 \le SOE_{H_2,t} \le SOE_{H_2,\max}$$

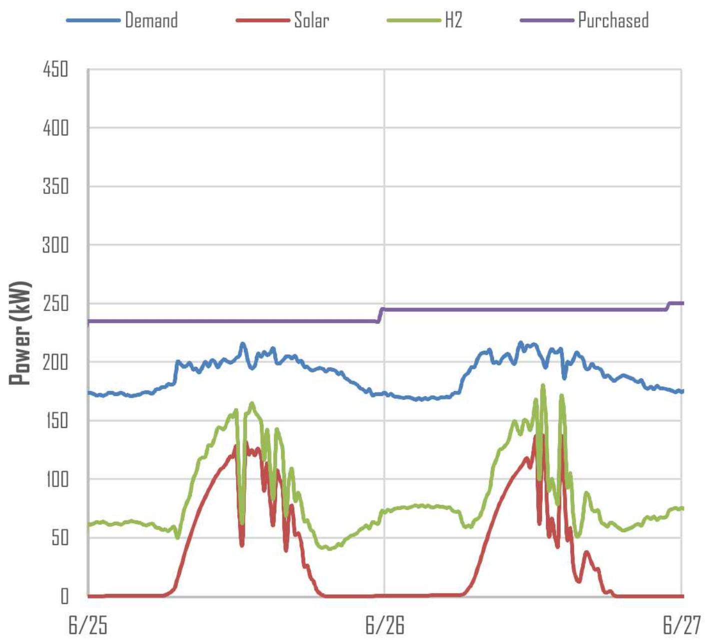
$$P_{H_2,t} - \alpha_{H_2,t} \cdot P_{H_2,\max} \le 0$$

$$P_{H_2,t} - 0.1 \cdot \alpha_{H_2,t} \cdot P_{H_2,\max} \ge 0$$

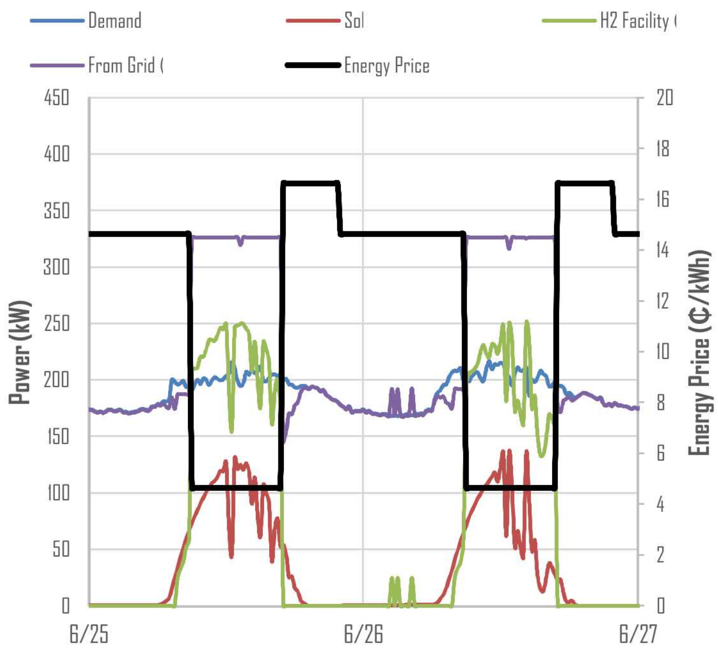
$$S_{t+} - S_{t-} = P_{FG,t} - P_{FG,t-1}$$

Example Analysis – NELHA Research Campus

Optimal Load Scheduling



Fixed Energy Rate



Time-of-use Energy Rate

Example Analysis – NELHA Research Campus

Hydrogen production scheduling would save $25,000/year

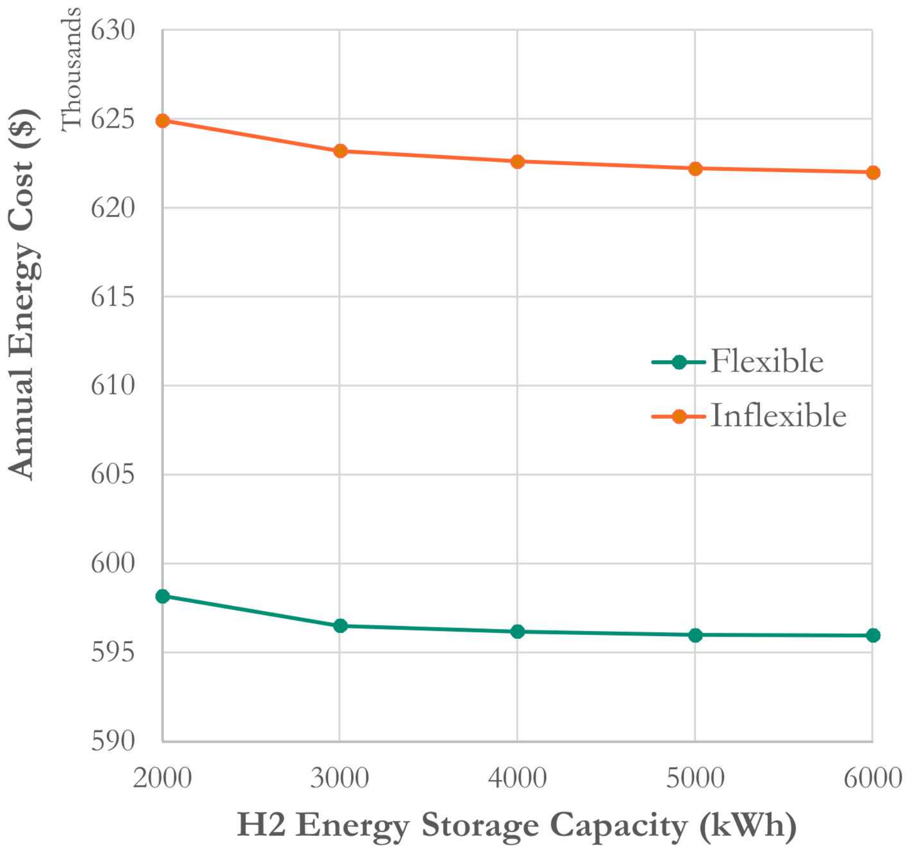
- HNEI has designed controls for flexible operation
- Sandia will assist in the implementation of site measurements and controls to realize savings
- System starting operations in early 2020

Demand response fulfills the roles of energy storage in this case

- Flattens daily demand profile
- Load shifting in TOU case

Ongoing analyses for NELHA / HNEI

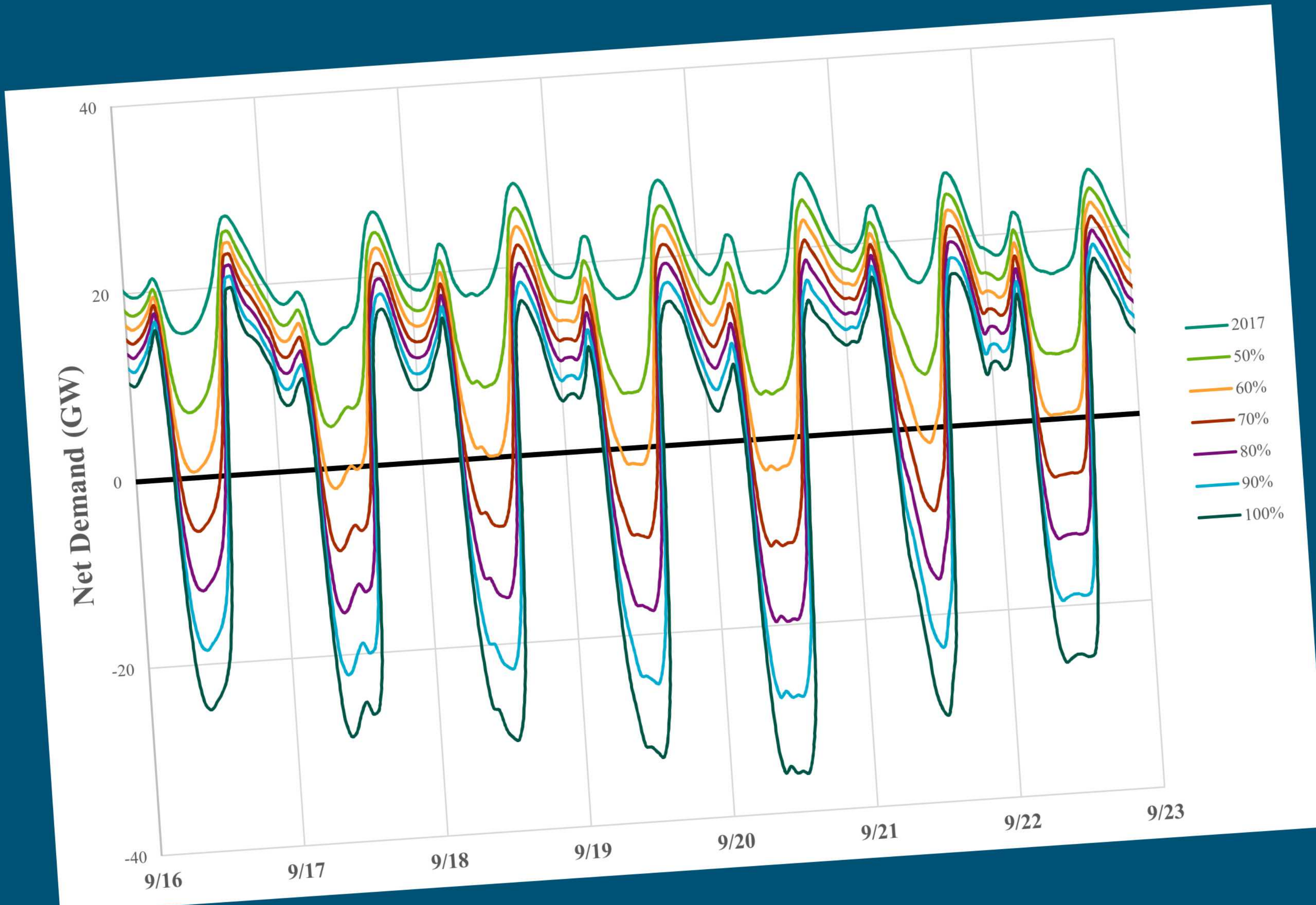
- Optimal scheduling with variable efficiencies
- Potential microgrid for NELHA campus



Questions?

Energy Storage is a major Crosscut at the lab.
Wide ranging R&D covering energy storage technologies with applications in the grid, transportation, and stationary storage
20+ staff, 10+ post docs, 22 University partners, close industry collaboration

Backup Slides



Backup Slides