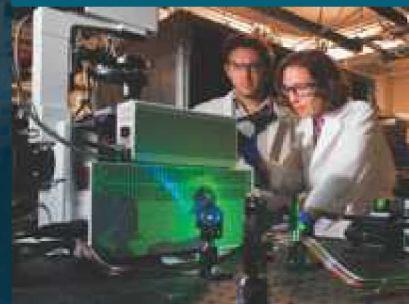


Energy Storage Research at Sandia

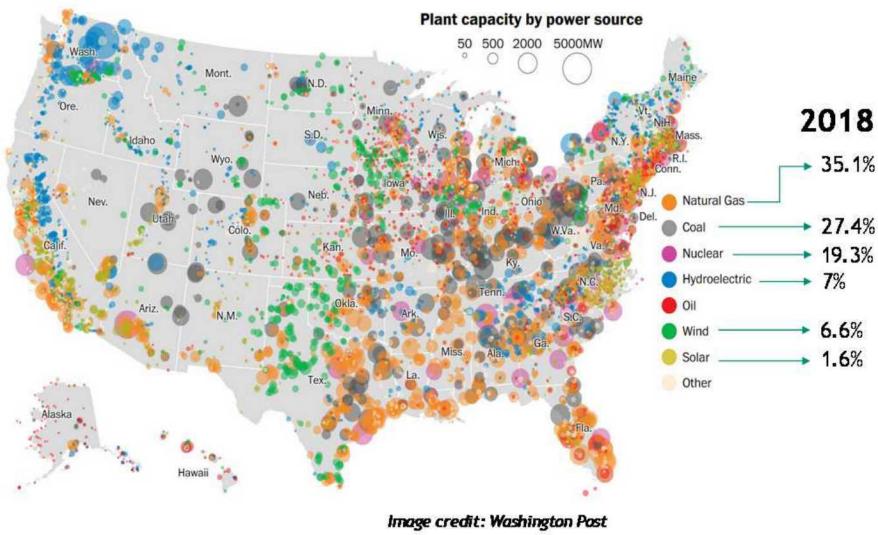
Alexander Headley

SAND2019-13905PE

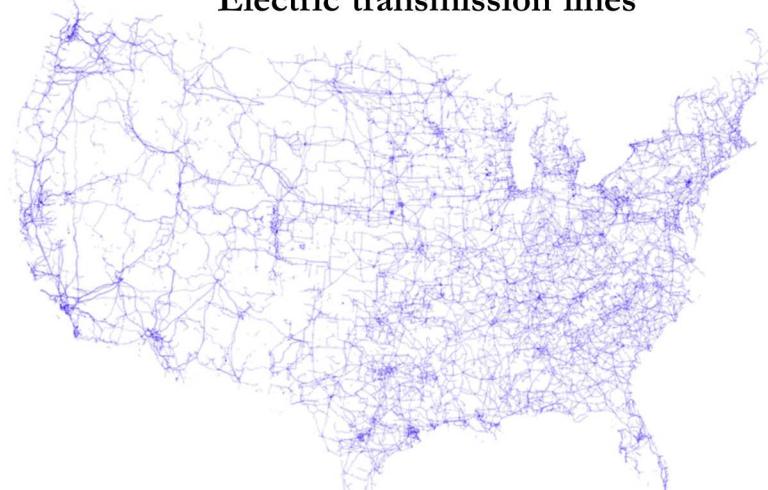
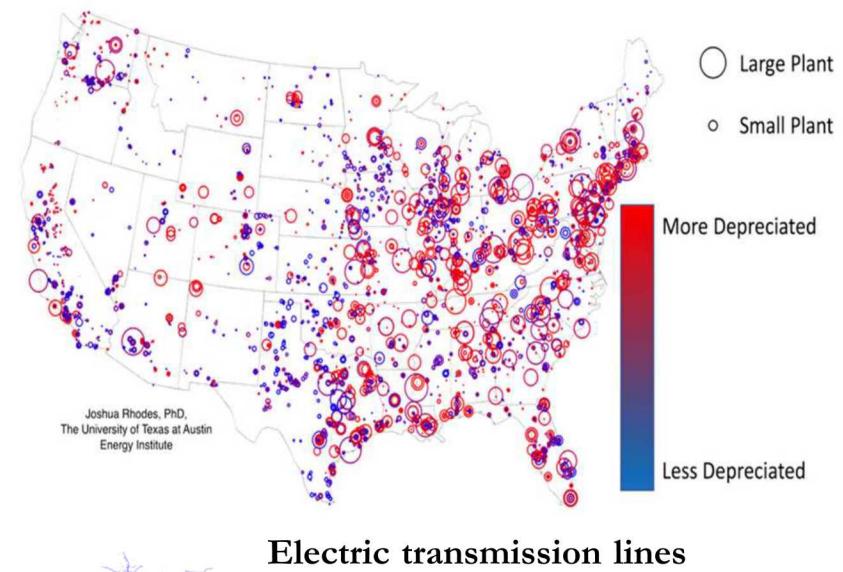


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U.S. Electric Grid Today



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

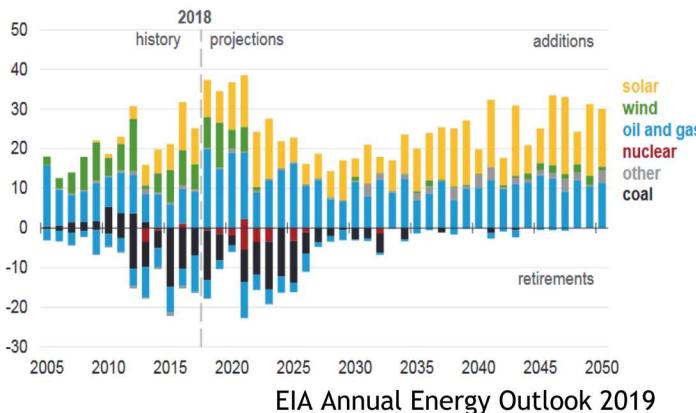


Growth of NG, Renewables, Cost Reductions

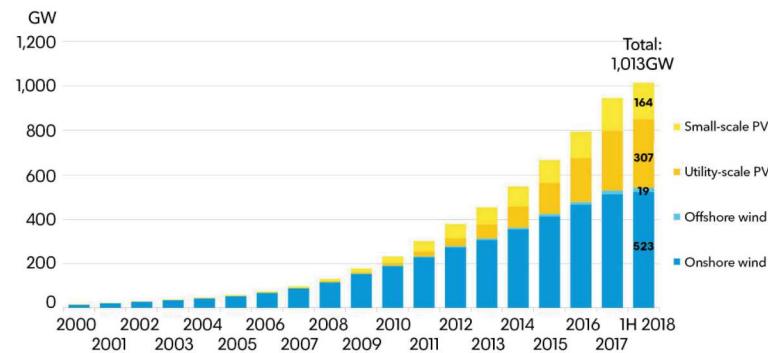


Capacity Additions and Retirements

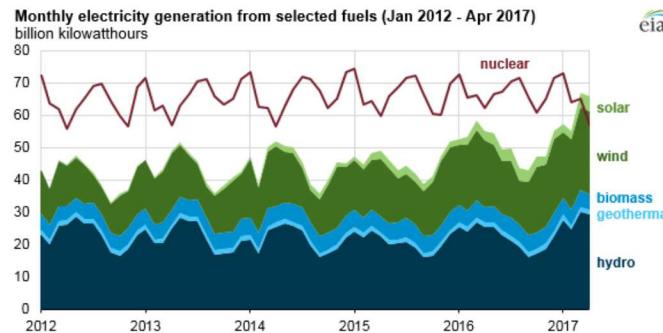
Annual electricity generating capacity additions and retirements (Reference case)
gigawatts



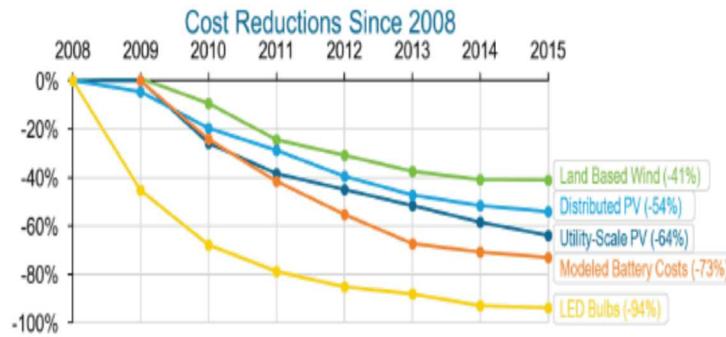
Cumulative global solar and wind capacity (June 2018)



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

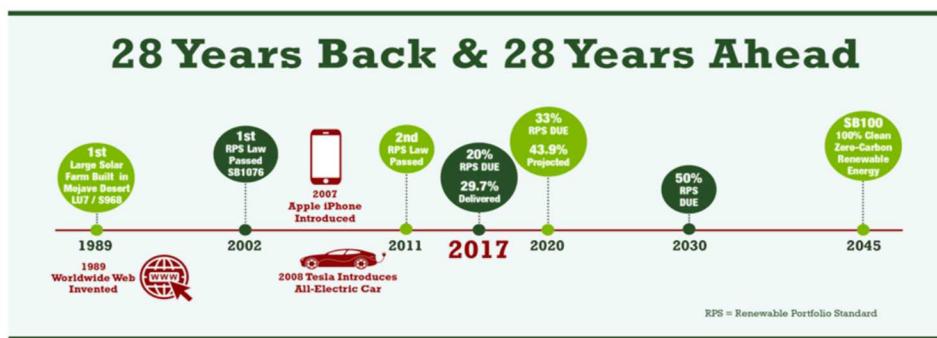
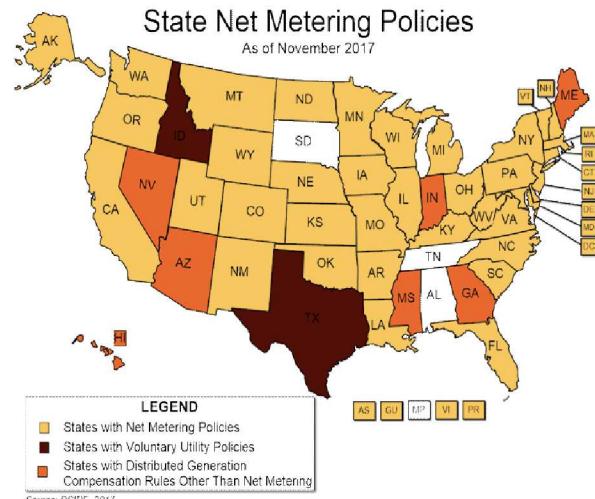


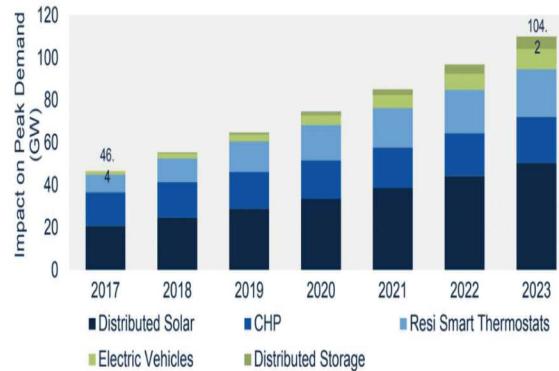
Image Source: California Senate

- 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.



US DER and Connected Devices Impact Expected to More Than Double from 46 GW to 104 GW

US DER and Connected Device Impact on Peak Potential, 2017-2023



Source: GTM Research and US DOE

Role of Energy Storage in the Grid

Grid resiliency and reliability

Improving power quality

Improving the efficiency of existing generation fleet

Demand management

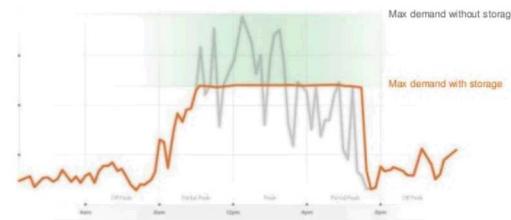
Renewable integration

Transmission & Distribution upgrade deferral

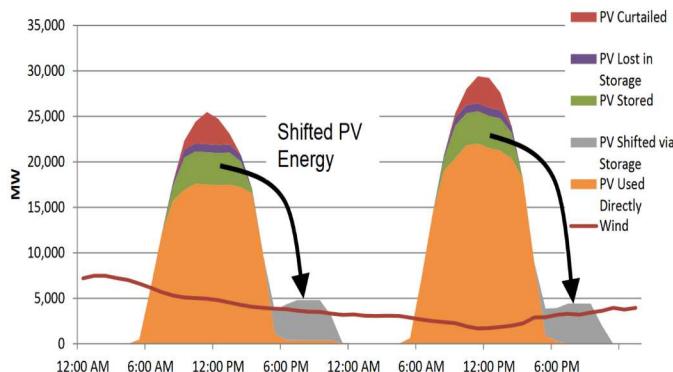
Off-grid applications



Mitigate \$79B/yr in commercial losses from outages

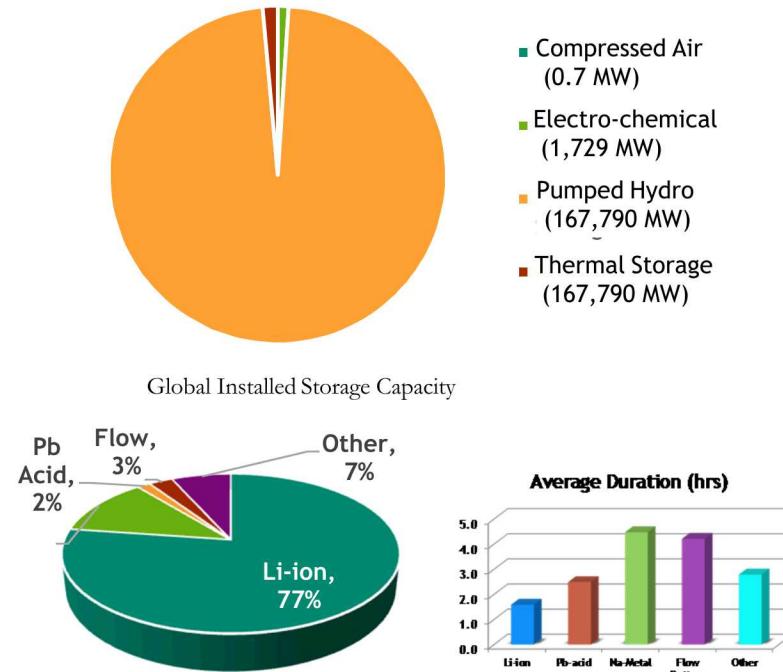


Reduce commercial and industrial electrical bills through demand charge management. 7.5 million U.S. customers are enrolled in dynamic pricing (EIA 2015)



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

Energy Storage in the Grid Today



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

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

Regulatory Outreach

Collaborating with States and other National Labs
State Policy Analysis

Safety & Reliability

Testing, Analysis, Standards, Protocols

Demonstration Projects

Support, Analysis, Implementation, Monitoring

Power Electronics

Reduce installed cost and footprint
Improve control capability
Increase reliability

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



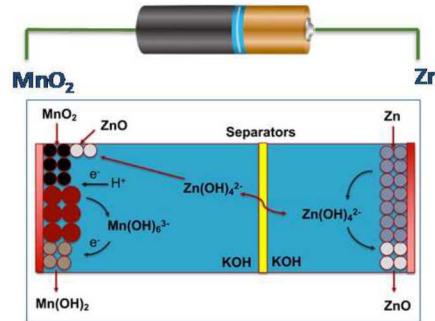
SCE Tehachapi plant, 8MW, 32MWh

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

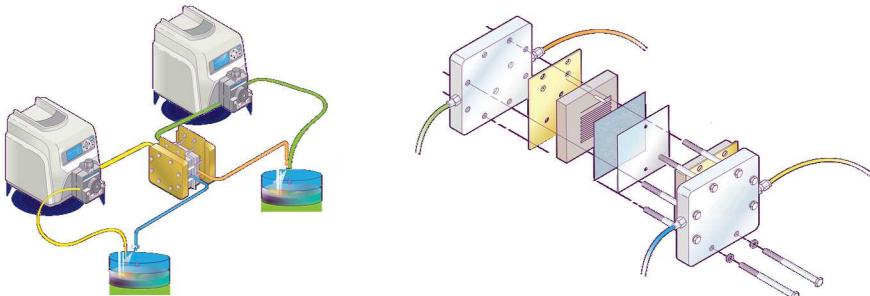
ZINC BATTERIES



- Developed permselective polymer separators to block zinicate 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



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

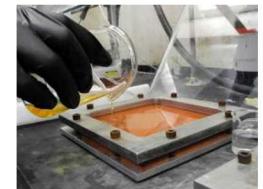
MEMBRANES

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

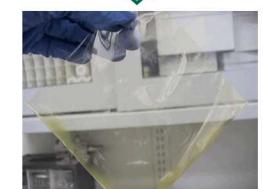
Currently looking for commercial partners



Solvent cast



Film





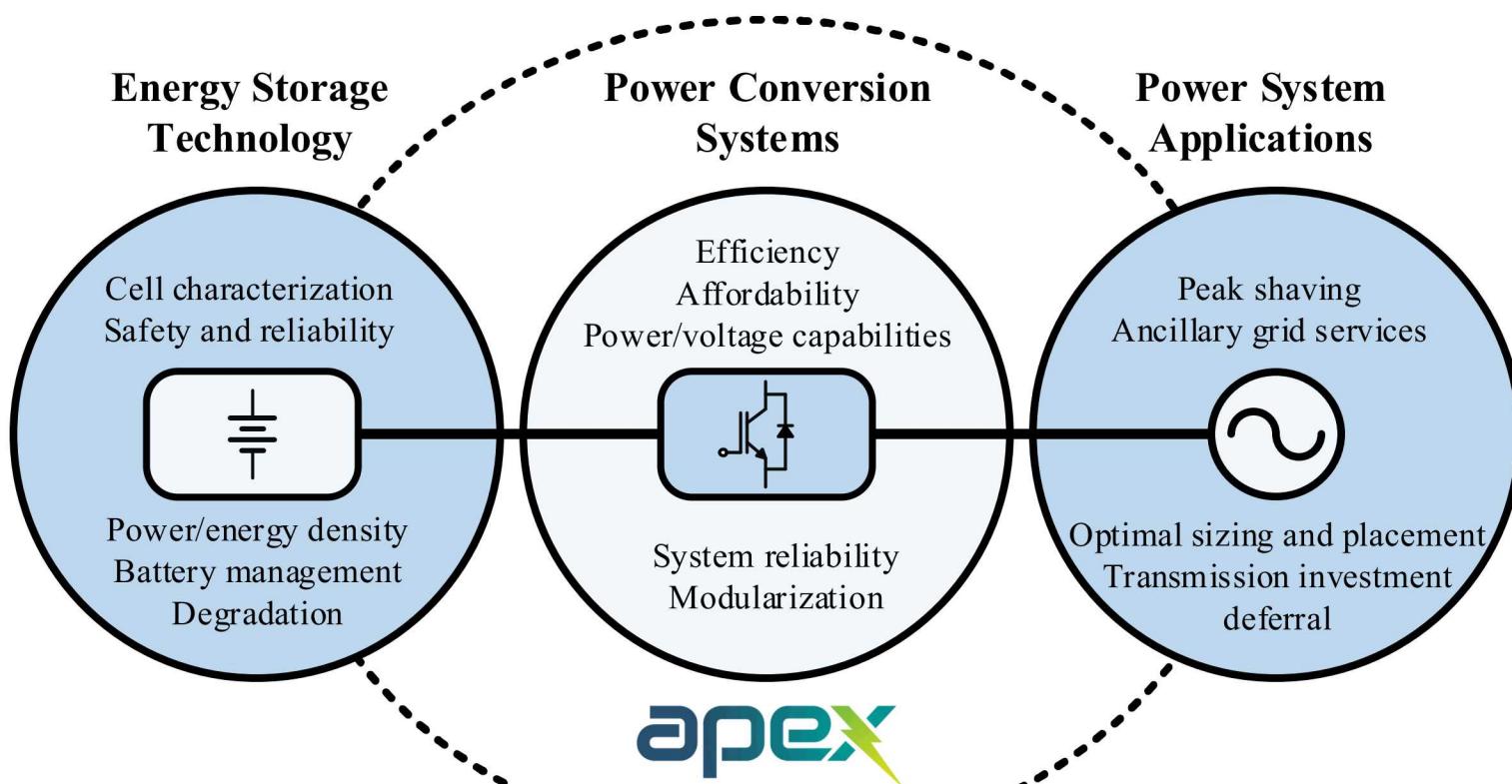
Power Electronics Area



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





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

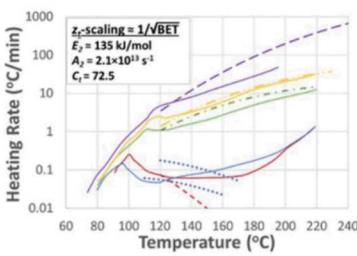
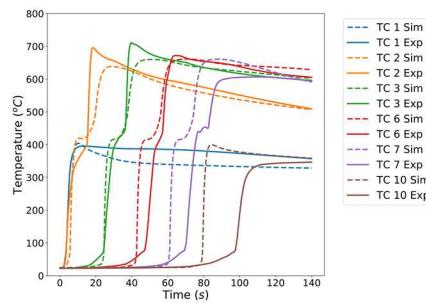


Systems Safety & Reliability

Modeling

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

Models for thermal runaway propagation in pouch cells

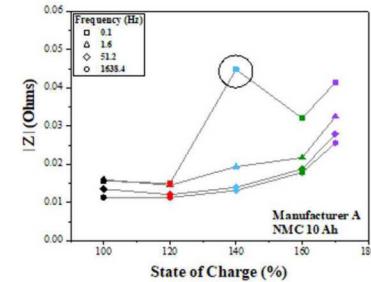
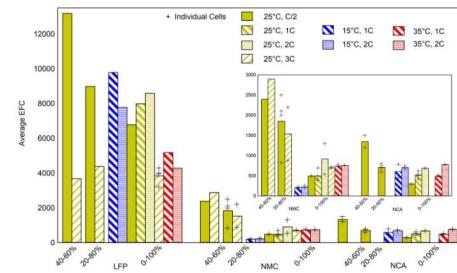


Comprehensive models of lithiated graphite and metal oxide cathode decomposition

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

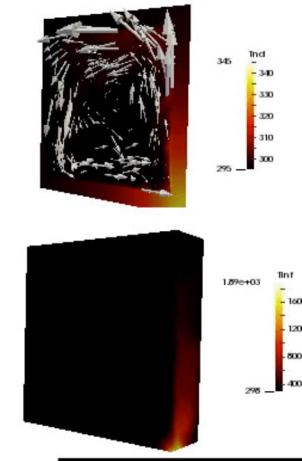
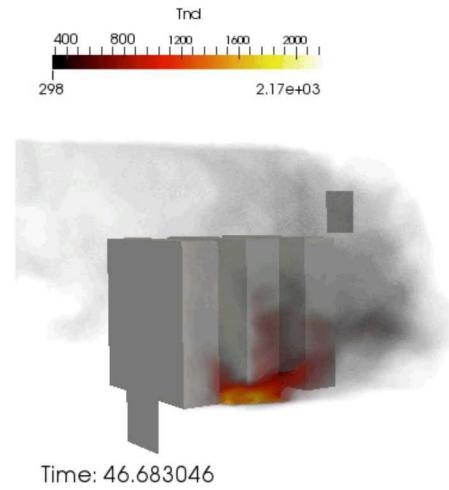
Approaches to engineered safety

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

LiCoO₂ 3Ah pouch cells

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

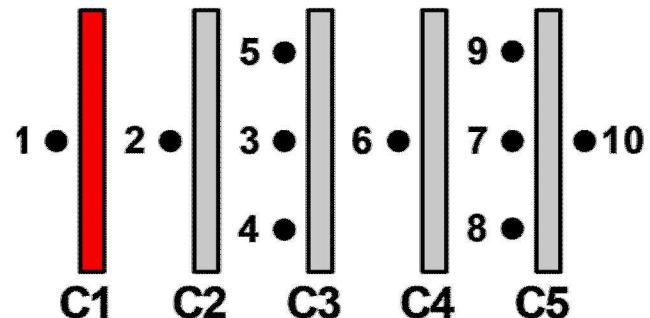
- Spacer thicknesses between 1/32" and 1/8"
- State of charge (SOC) between 50% and 100%

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

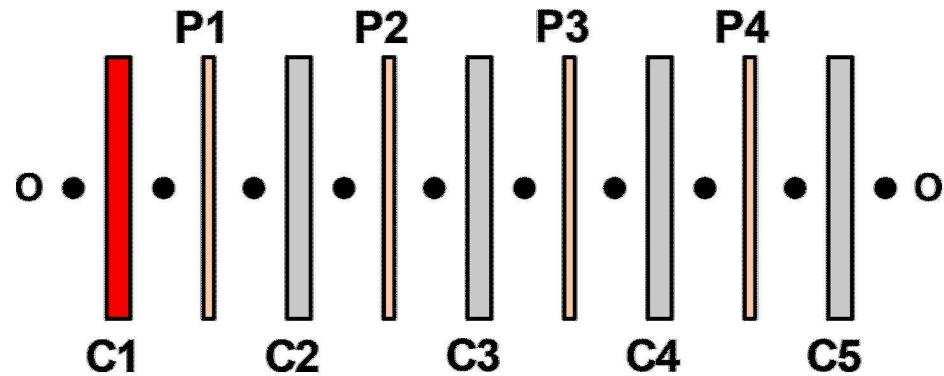
Thermocouples (TC) between cells and spacers (if present)



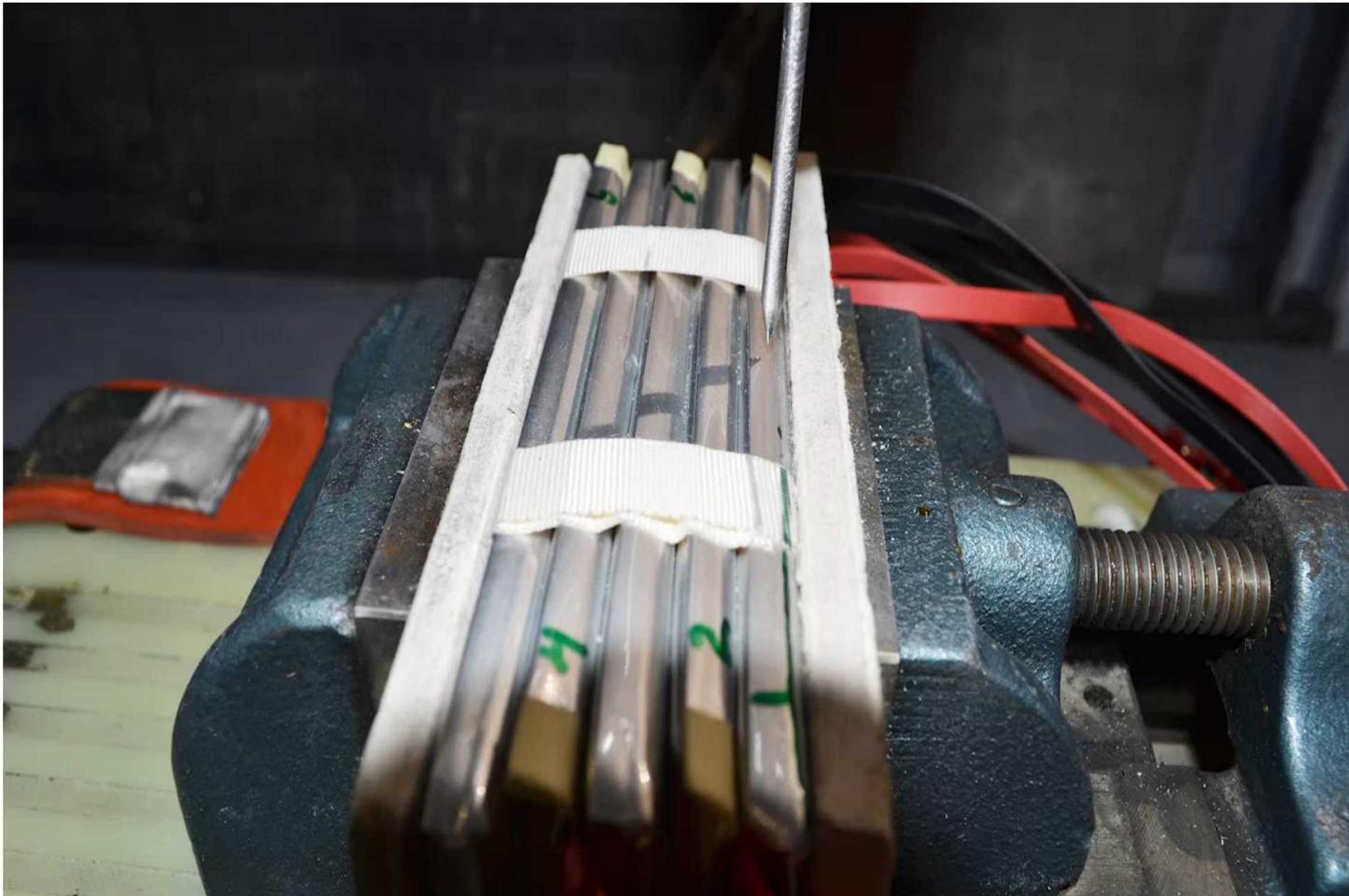
Thermocouple Locations



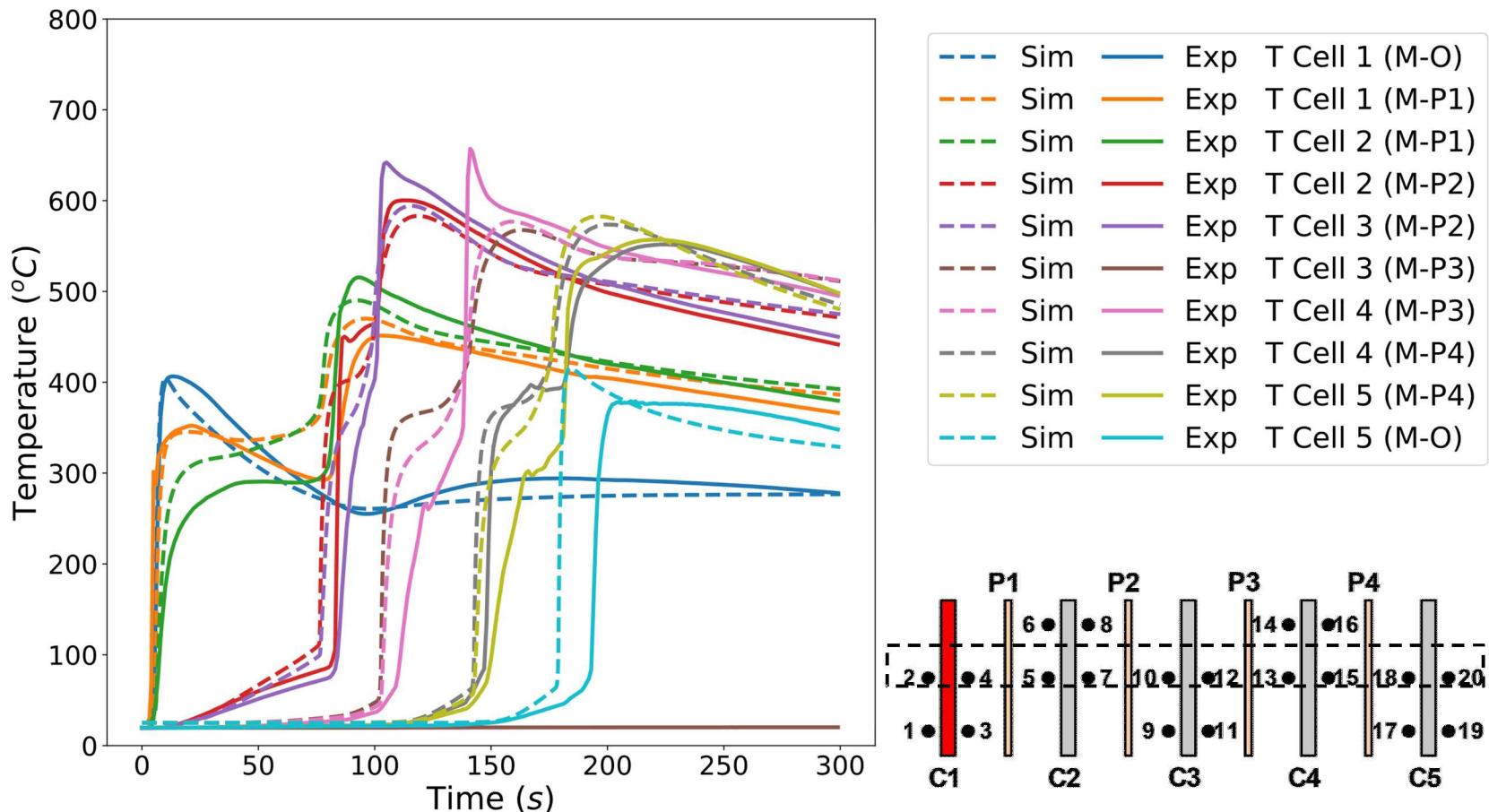
Thermocouple Locations with spacer plates



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

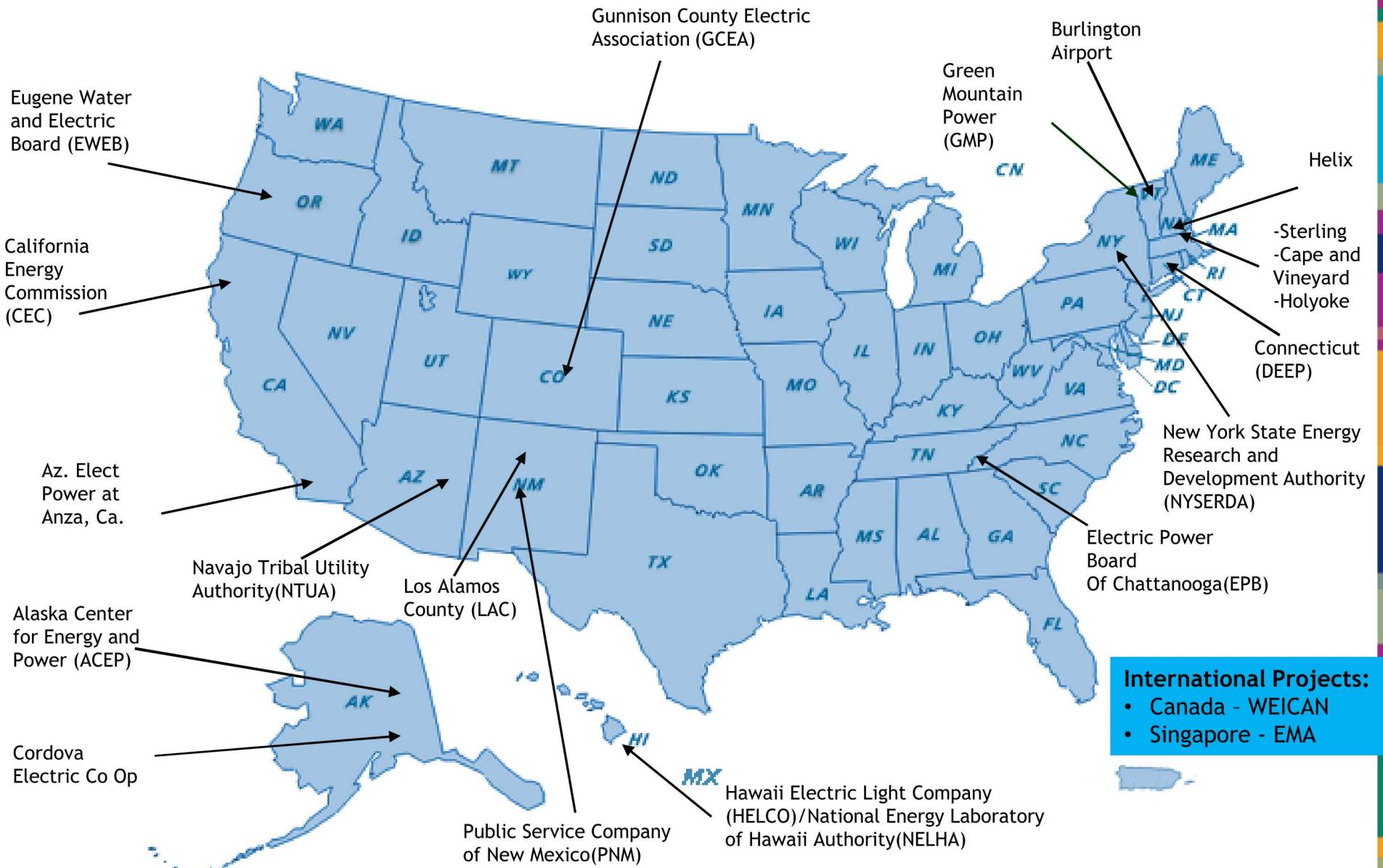
Monitor and analyze operational ES Projects

- Application validation
- System optimization
- Operational performance analysis

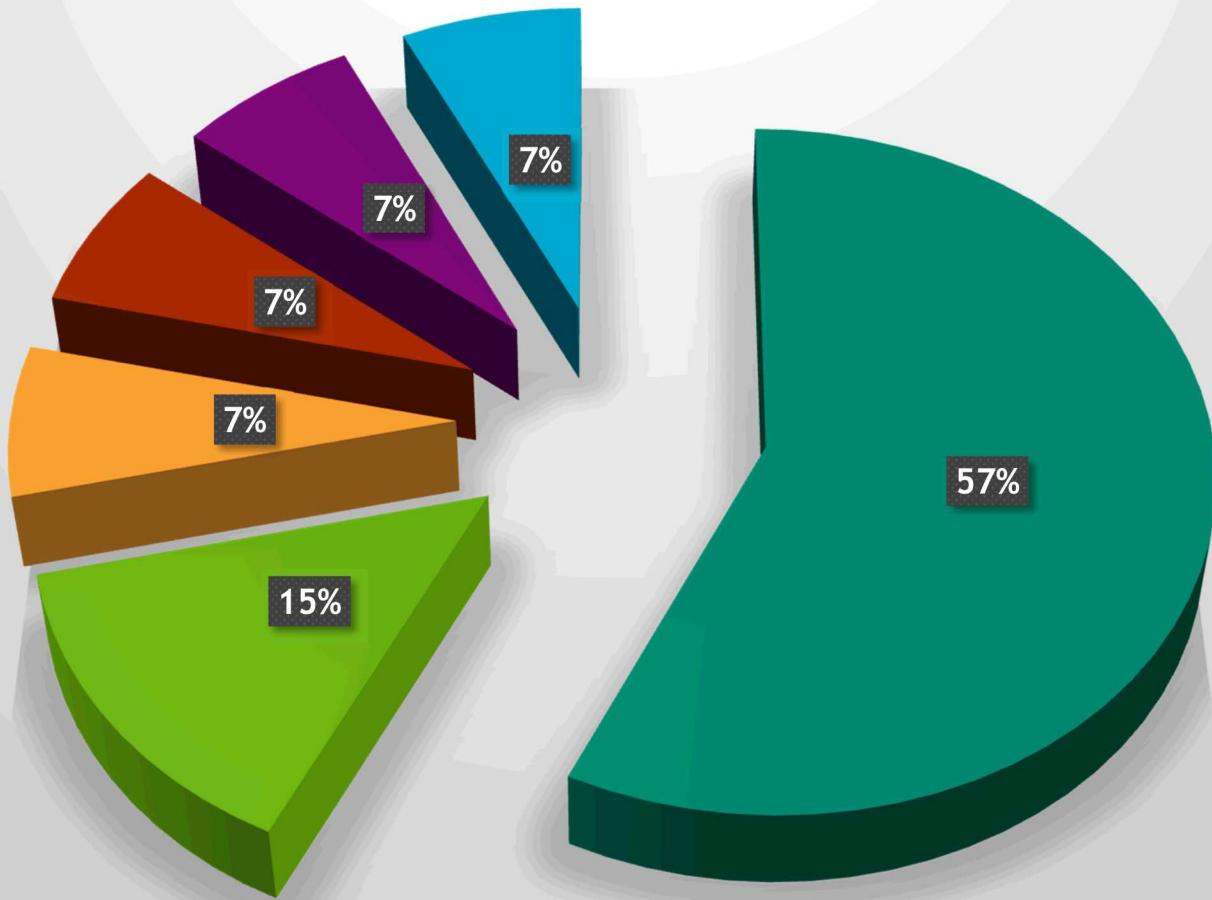
Develop public information programs

Inform the Public and encourage investment.

Energy Storage Demonstration Projects



Energy Storage Project Technologies



■ Li-Ion ■ ZnMnO₂ ■ Advanced Pb-Acid ■ Flywheel ■ NaS ■ REDOX Flow

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

Raymond H. Byrne¹, Sean Hirschfeld¹, David R. Domer², Todd Blankens-Paull³ and Jim Glynn⁴
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³Sterling Municipal Light Department, Sterling, MA 01564, USA
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⁵U.S. Department of Energy, Office of Electricity Delivery and Reliability, Washington, DC 20585, USA

Abstract—The Sterling Municipal Light Department (SMLD) is a progressive public power utility located 10 miles NNE of Worcester, Massachusetts in the Town of Sterling, SMLD has a long history of investment in renewable generation, with approximately 35% of generation coming from renewable sources. The goal of this project is to identify potential benefits and value added to the utility from energy storage. The project will demonstrate the use of energy storage to reduce frequency regulation, minimize its monthly or winter load, and derive its capacity payments to ISO New England, and grid credits.

Index Terms—energy storage, ISO New England

I. INTRODUCTION

The Sterling Municipal Light Department (SMLD) is a progressive public power utility located 10 miles NNE of Worcester, Massachusetts in the Town of Sterling. The primary heating was originally the 1863 Sterling High School, built in the Town of Sterling for over 100 years, there are now over 1000 students attending the high school, middle school, and elementary schools. Currently, there are 4000 students attending approximately 1400 units of residential load. The SMLD is a member of ISO New England (ISO-NE) and a wholesale supplier of power with power purchases from generation throughout New England and New York.

The SMLD has a long history of investment in renewable generation. Approximately 35% of power generation comes from renewable sources, with approximately 25% from Solar accounts for approximately 30% of the department's peak load. The 1-megawatt solar installations went on line in 2007, placing SMLD at the top of the Solar Electric Power Association Top 10 utility rankings for the year for new solar units per customer [1]. SMLD currently has 3 MW of solar installed.

Power purchase of energy storage in ISO-NE is described in [2], where the authors discuss the integration of Renewable and Energy Storage for frequency regulation in regional and inter-jurisdictional markets. The utility in this work is purchased for 3 MW of battery storage at 100% NREL. Beacon Power's testing found that on average, a 1 MW system incurs 100 kWh per hour, which corresponds to 6.33 frequency change/charge cycles per year. Over a 20 year life, this results in approximately 123,000 full charge/discharge cycles. The authors

argue that the charge/discharge profile would be difficult for classical energy storage systems.

The methodology for estimating maximum potential revenue from an energy storage system participating in energy and frequency markets is outlined in [3]. The problem was solved for the SMLD using the 100% NREL battery model for California Independent System Operator (CAISO) data were presented. For the CAISO data, frequency regulation provided significantly more revenue opportunity than storage. An analysis of potential revenue from energy storage in the Electrical Reliability Council of New England (ERCN) is presented in [4]. An analysis of all load areas in ISO-NE for 2011 found that the highest potential revenue was from the load with the highest annual potential revenue. This analysis found significantly more potential revenue than storage. Because the only real market for frequency regulation in ISO-NE and the majority of revenue was from frequency regulation, the location of the system does not impact potential revenue.

The analysis also highlights the variability from year to year in potential revenue. An energy storage system had a revenue trial in 2010 and 2011. The system was deployed in 2011, and had an approximately 10% higher potential revenue than storage (over three times the 2010/2011 potential revenue). An analysis of the ISO-NE regulation, which includes performance, is presented in [5]. Once again, frequency regulation provided significantly more potential revenue than storage in ISO-NE for the data analyzed. An early summary of potential revenue from various markets is listed in [6].

The goal of this paper is to determine the potential revenue of external energy storage for the SMLD. Revenue considered in this study include energy arbitrage, frequency regulation, reduction in monthly network load, reduction in capacity payments to ISO New England, and grid stability.

The paper is organized as follows. Section II provides an overview each potential revenue. Section III summarizes the potential benefits as summarized in Section V.

II. OVERVIEW OF REVENUE STREAMS

There are many potential benefits from external energy storage [7]. This paper considers benefits specific to SMLD, and includes energy storage, frequency regulation, reduction

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

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

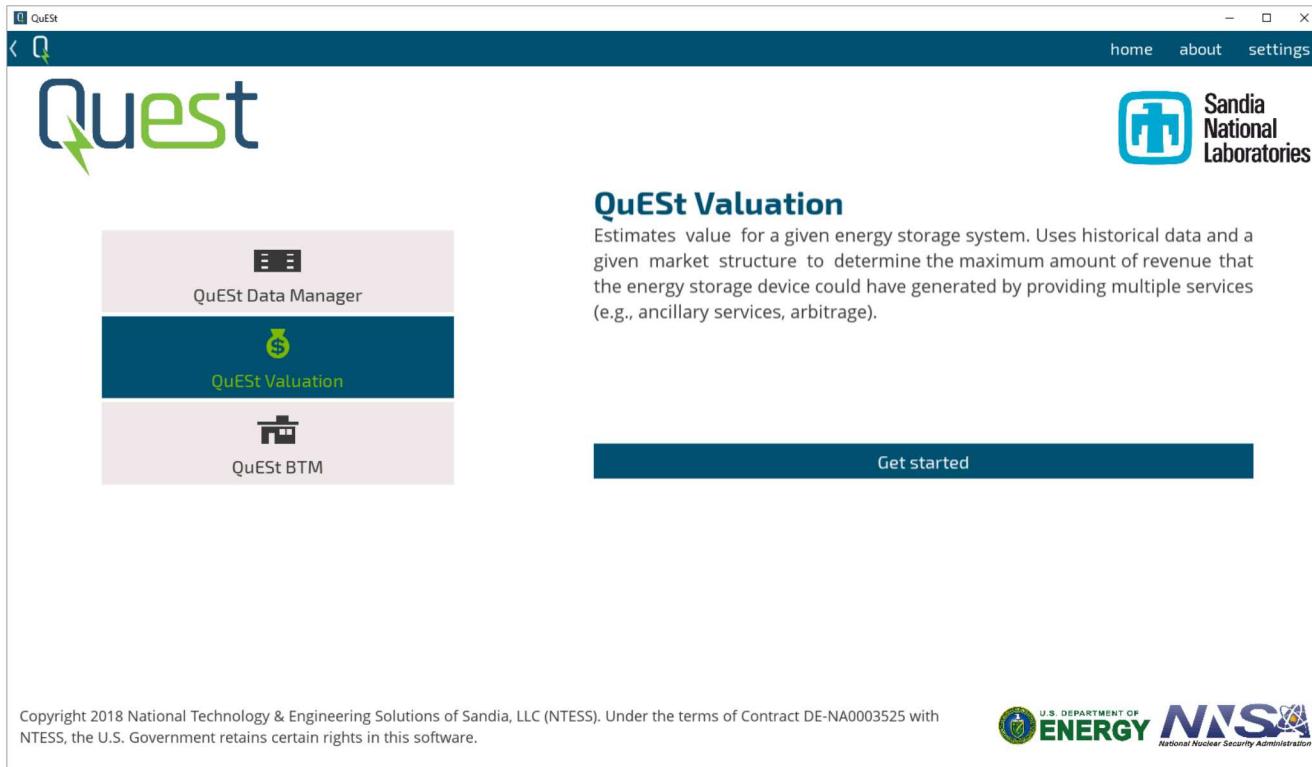
Enhancing grid reliability and resiliency

- 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?



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QuEST Valuation
 Estimates value for a given energy storage system. Uses historical data and a given market structure to determine the maximum amount of revenue that the energy storage device could have generated by providing multiple services (e.g., ancillary services, arbitrage).

Get started

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

- 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



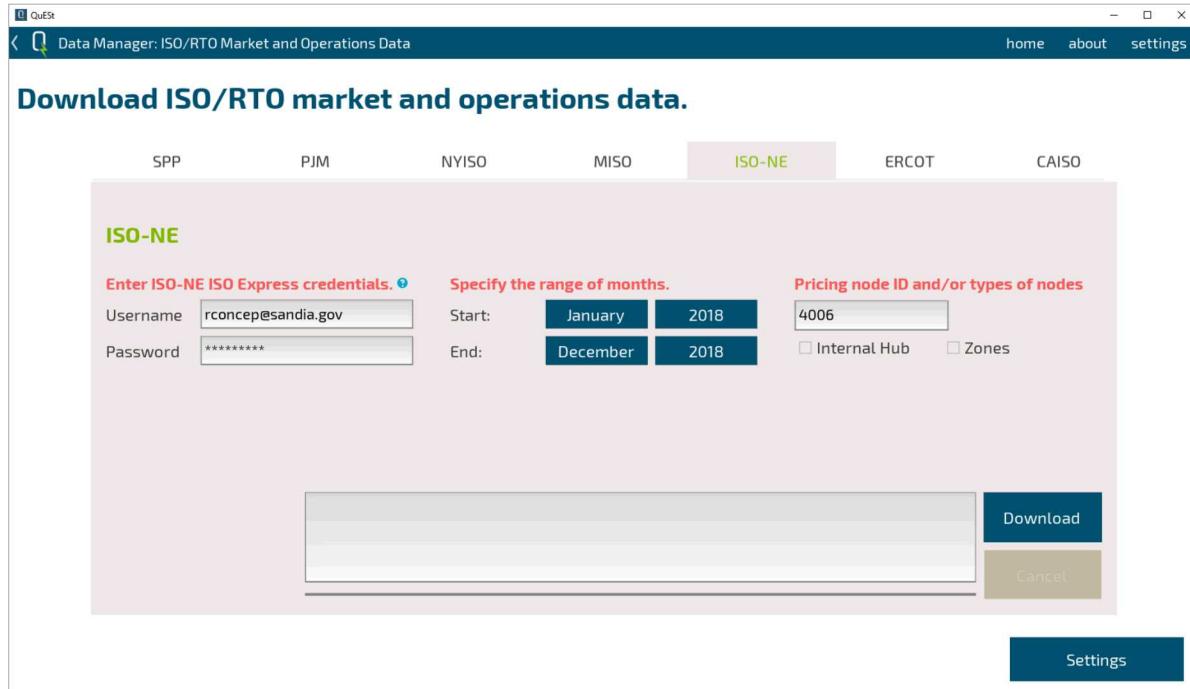
Why QuESt?

- 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

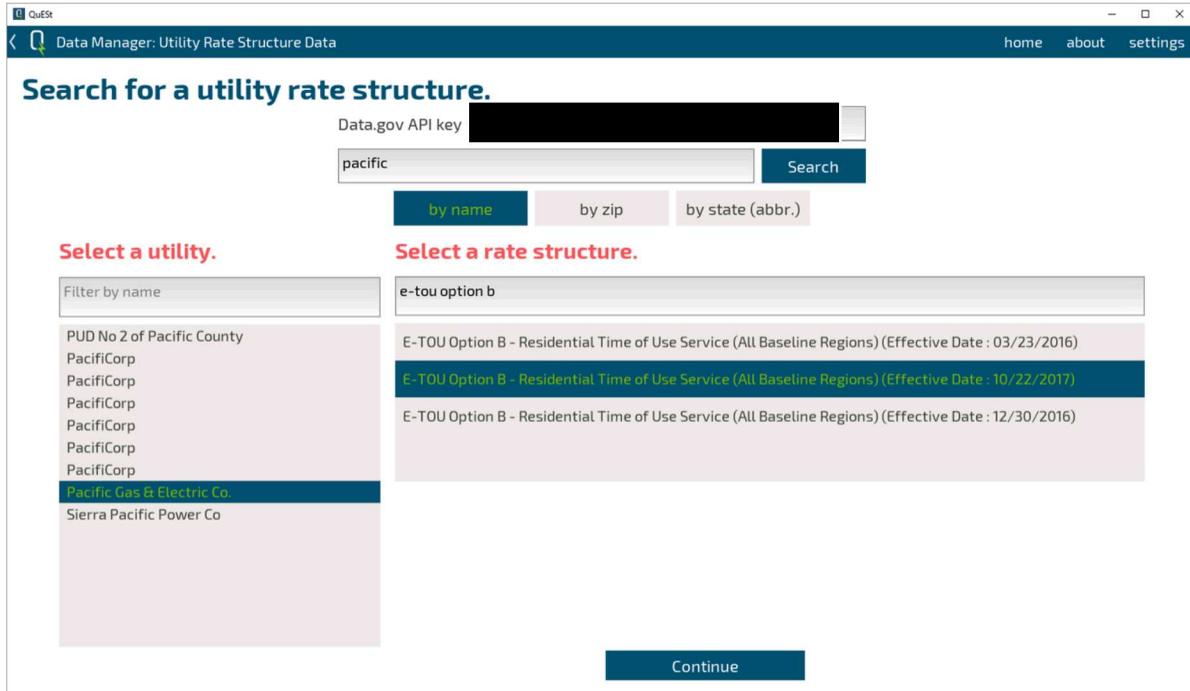


QuEST Data Manager



- 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



The screenshot shows a search interface for utility rate structures. At the top, there is a search bar with the placeholder text "Data.gov API key" and a redacted value. Below the search bar is a text input field containing "pacific" and a "Search" button. Underneath the search bar are three buttons: "by name" (highlighted in blue), "by zip", and "by state (abbr.)". The main search results are divided into two sections: "Select a utility." and "Select a rate structure." The "Select a utility." section on the left lists several utility names, with "Pacific Gas & Electric Co." and "Sierra Pacific Power Co." highlighted in blue. The "Select a rate structure." section on the right lists rate structures, with "E-TOU Option B - Residential Time of Use Service (All Baseline Regions) (Effective Date : 03/23/2016)" and "E-TOU Option B - Residential Time of Use Service (All Baseline Regions) (Effective Date : 10/22/2017)" highlighted in blue. At the bottom center is a "Continue" button.

- 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

Verify the energy rate structure.

| Period | Rate [\$/kWh] |
|--------|---------------|
| 0 | 0.26029 |
| 1 | 0.36335 |
| 2 | 0.20708 |
| 3 | 0.22588 |

Weekday

| Month | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 | | | |
|-------|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|---|---|---|
| Jan | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Feb | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Mar | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Apr | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| May | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Jun | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Jul | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Aug | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Sep | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Oct | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Nov | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Dec | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Jan | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Feb | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Mar | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Apr | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| May | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Jun | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Jul | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Aug | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Sep | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Oct | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Nov | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Dec | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |

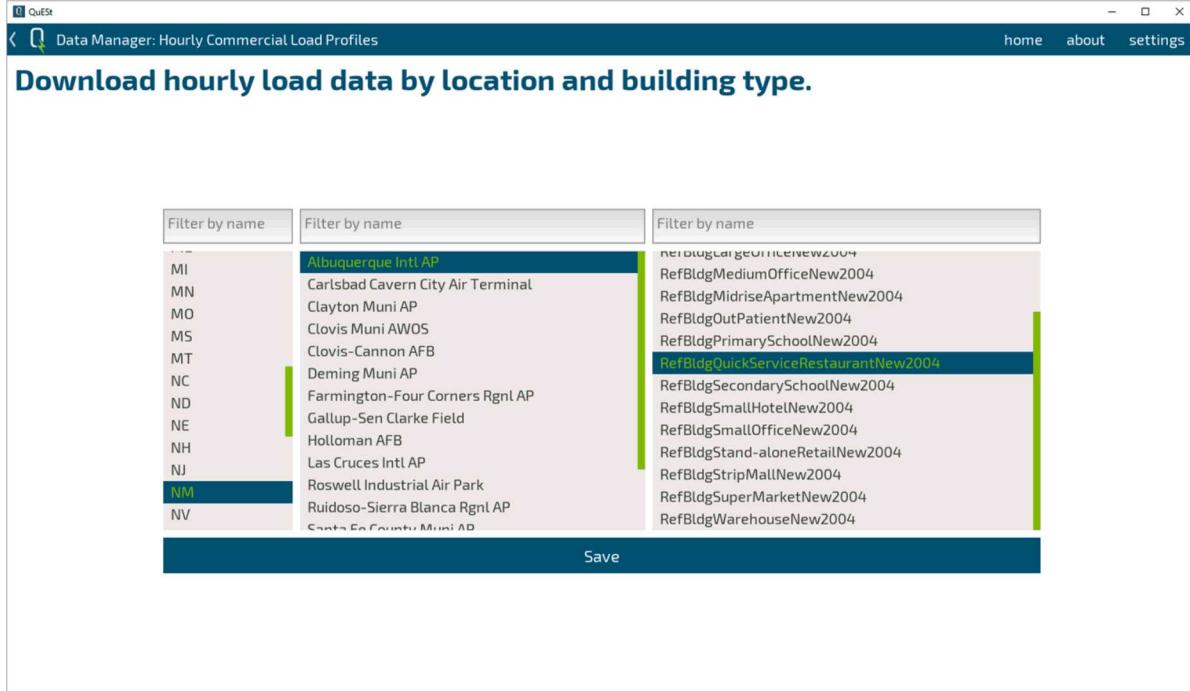
Weekend

| Month | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 | | | | |
|-------|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|---|---|---|---|
| Jan | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Feb | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Mar | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Apr | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| May | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Jun | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Jul | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Aug | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Sep | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Oct | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Nov | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Dec | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |

Previous Continue

- 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



The screenshot shows a web-based application titled "QuEST Data Manager: Hourly Commercial Load Profiles". The main heading is "Download hourly load data by location and building type." Below this, there are three filter boxes: "Filter by name" for states (MI, MN, MO, MS, MT, NC, ND, NE, NH, NJ, NM, NV), "Filter by name" for locations (Albuquerque Intl AP, Carlsbad Cavern City Air Terminal, Clayton Muni AP, Clovis Muni AWOS, Clovis-Cannon AFB, Deming Muni AP, Farmington-Four Corners Rgnl AP, Gallup-Sen Clarke Field, Holloman AFB, Las Cruces Intl AP, Roswell Industrial Air Park, Ruidoso-Sierra Blanca Rgnl AP, Santa Fe County Muni AP), and "Filter by name" for building types (RefBldgLargeOfficeNew2004, RefBldgMediumOfficeNew2004, RefBldgMidriseApartmentNew2004, RefBldgOutPatientNew2004, RefBldgPrimarySchoolNew2004, RefBldgQuickServiceRestaurantNew2004, RefBldgSecondarySchoolNew2004, RefBldgSmallHotelNew2004, RefBldgSmallOfficeNew2004, RefBldgStand-aloneRetailNew2004, RefBldgStripMallNew2004, RefBldgSuperMarketNew2004, RefBldgWarehouseNew2004). A "Save" button is at the bottom.

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

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

QuEST Data Manager

QuEST

Data Manager: Photovoltaic Power Profiles

home about settings

Search for a photovoltaic power profile.

Data.gov API key [REDACTED]

latitude The latitude of the site in the range (-90, 90). deg

longitude The longitude of the site in the range (-180, 180). deg

system capacity The nameplate capacity of the photovoltaic system. kW

losses The total system losses, including all sources, in the range (-5, 99). %

tilt angle The tilt angle of the PV surface. deg

azimuth angle The azimuth angle of the PV surface. deg

Standard Fixed (roof mounted)

san_fran_5kW

Save

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

QuEST

Wizard

home about settings

Select a market area to place the energy storage device in.

Different market areas can have different market structures, resulting in various opportunities for generating revenue.



IRC

Previous

Next

| ERCOT | PJM | MISO |
|-------|-------|------|
| NYISO | ISONE | SPP |
| CAISO | | |

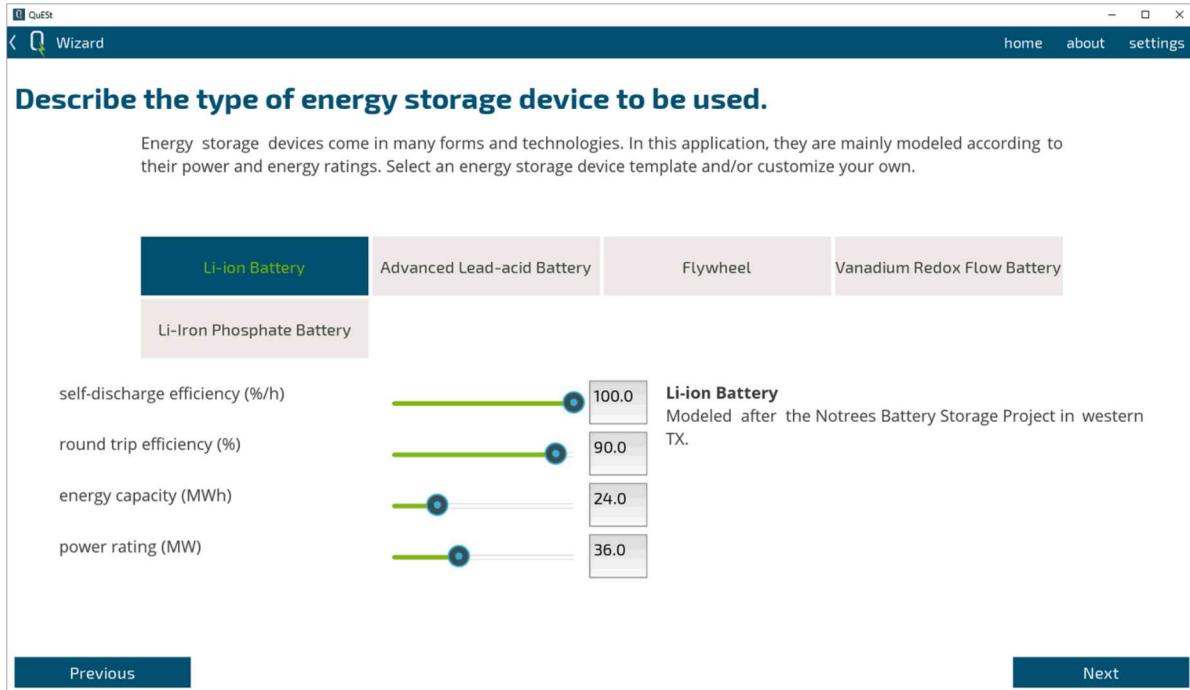
- Market area

- Arbitrage and Frequency Regulation streams

- Historical dataset to study

- Energy storage model parameters

QuEST Valuation



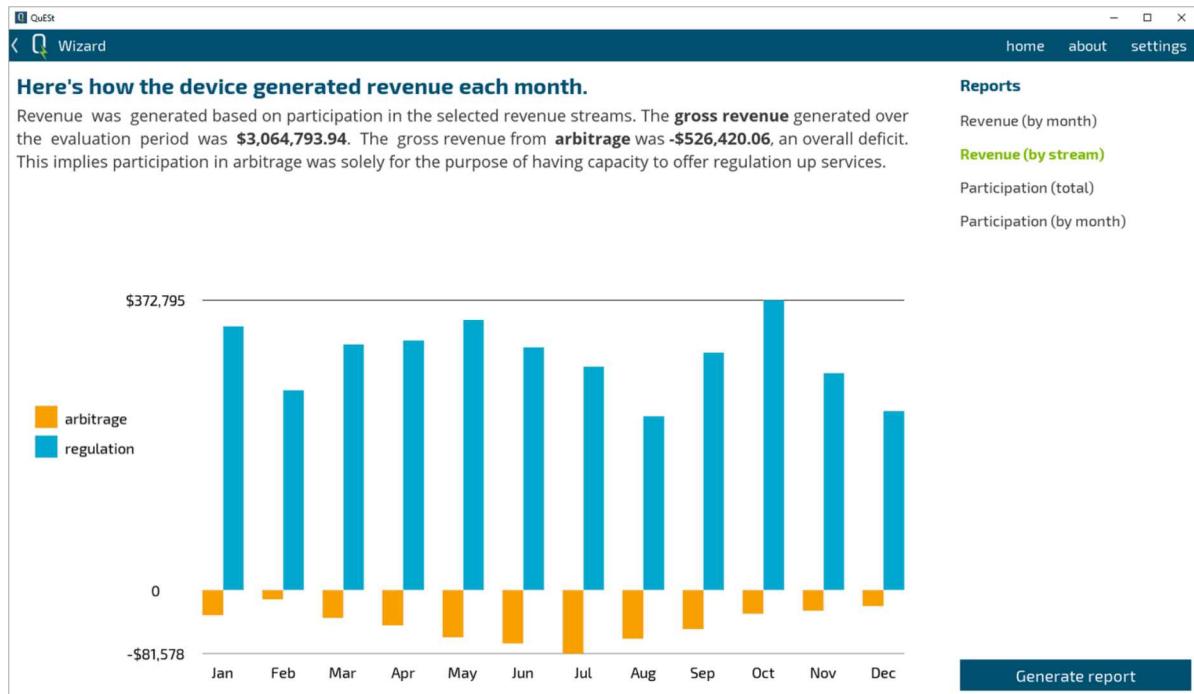
The screenshot shows the QuEST Wizard interface. The title bar reads "QuEST Wizard". The main content area has a heading "Describe the type of energy storage device to be used." Below this, a note states: "Energy storage devices come in many forms and technologies. In this application, they are mainly modeled according to their power and energy ratings. Select an energy storage device template and/or customize your own." A horizontal navigation bar at the top includes "home", "about", and "settings". Below the note, there are five tabs: "Li-ion Battery" (selected, highlighted in dark blue), "Advanced Lead-acid Battery", "Flywheel", and "Vanadium Redox Flow Battery". Under the "Li-ion Battery" tab, there is a sub-section titled "Li-Iron Phosphate Battery". The configuration parameters are as follows:

- self-discharge efficiency (%/h): 100.0
- round trip efficiency (%): 90.0
- energy capacity (MWh): 24.0
- power rating (MW): 36.0

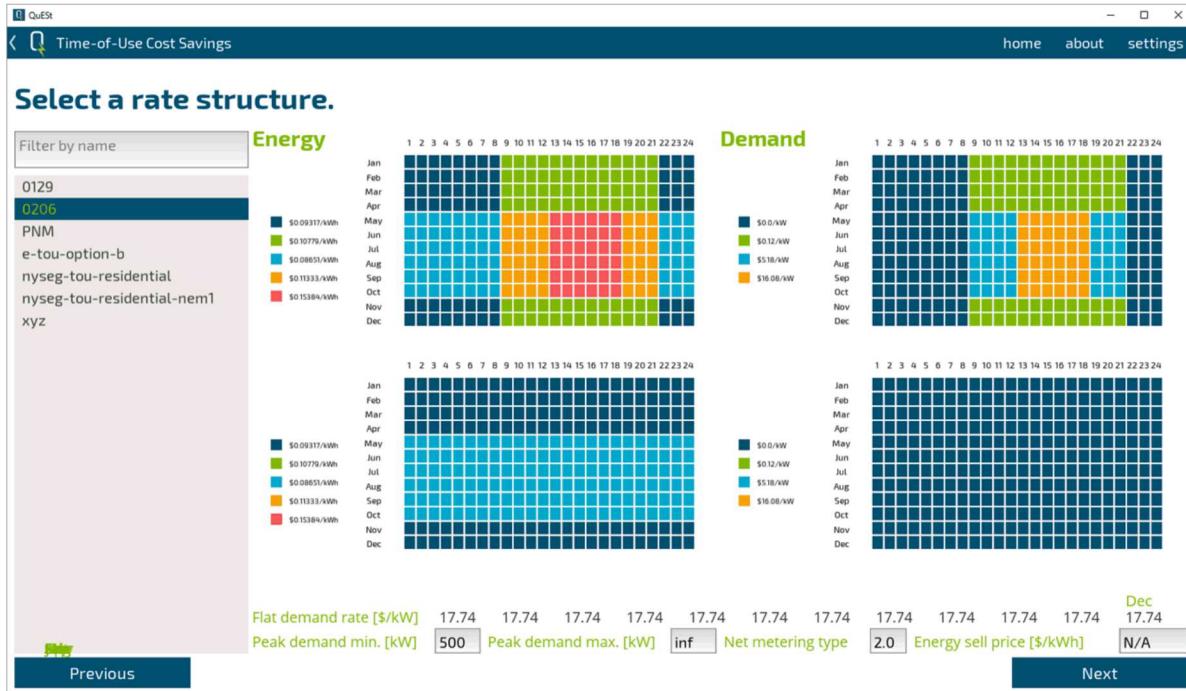
Below these parameters, a note says: "Modeled after the Notrees Battery Storage Project in western TX." At the bottom of the interface are "Previous" and "Next" buttons.

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

QuEST Valuation



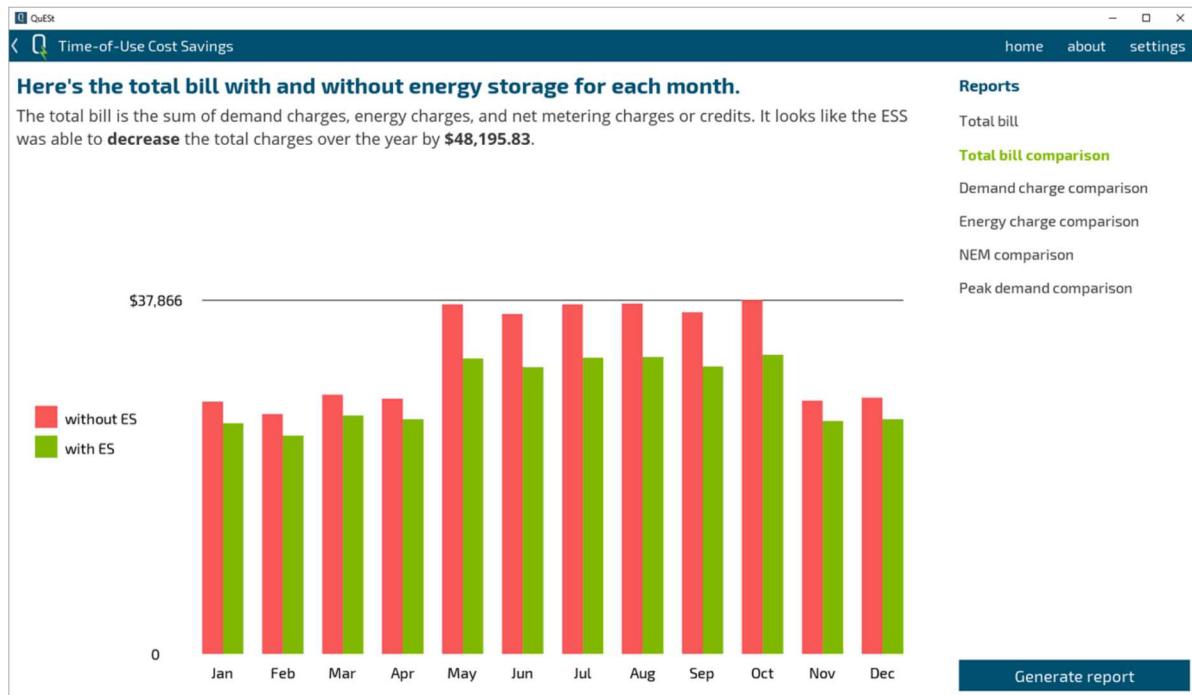
- Revenue by month
- Revenue by revenue stream
- Frequency of participation in each available revenue stream



- 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

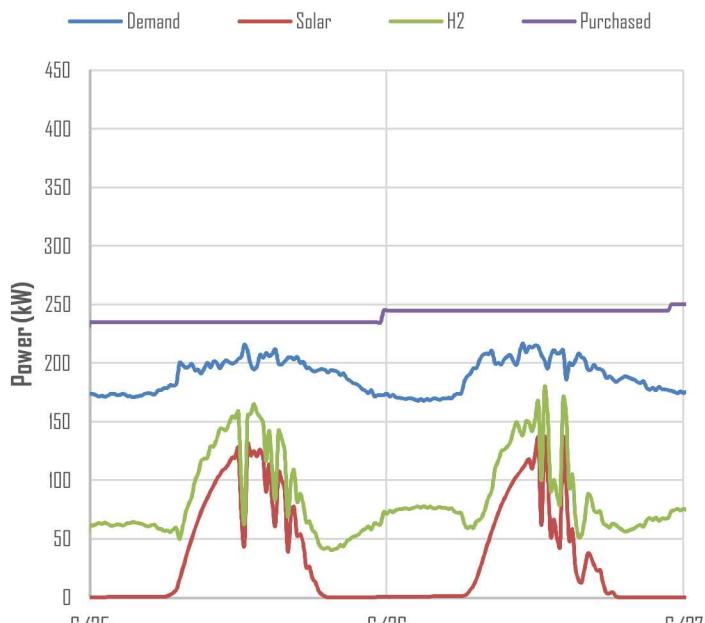
$$\begin{aligned}
 & \min_{P_C, P_D, P_{H_2}} \quad P_{peak} \cdot C_{Dem} + \sum_{t=1}^T P_{FG,t} \cdot \frac{\Delta t}{60} \cdot (C_{E,t} + C_{fixed,kWh}) + \frac{\sum_{t=1}^T S_{t+} + S_{t-}}{K} \\
 & \text{subject to} \quad SOC_t = SOC_{t-1} + \frac{\Delta t}{60} (P_{C,t-1} \eta_{RT} - P_{D,t-1}) \\
 & \quad P_{FG,t} = P_{Dem,t} + P_{H_2,t} + P_{C,t} - P_{D,t} - P_{sol,t} + P_{curt,t}
 \end{aligned}$$

Hydrogen Production Model

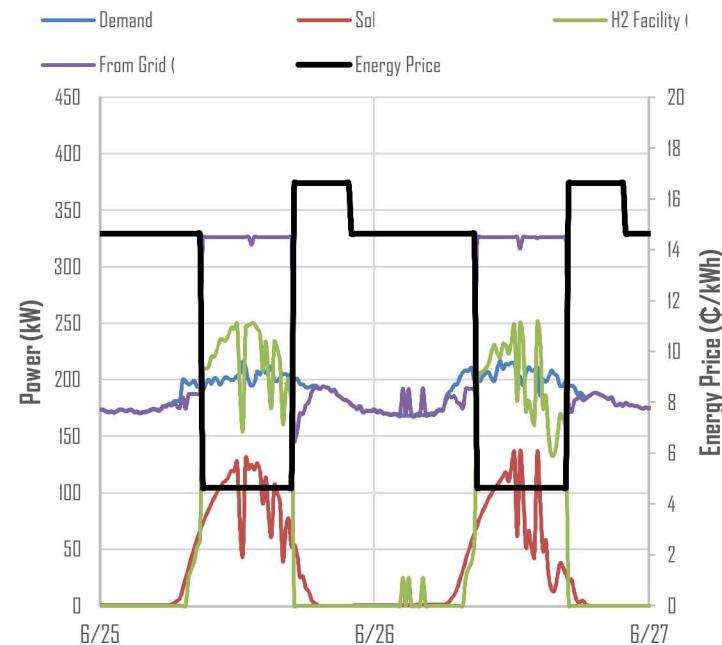
$$\begin{aligned}
 SOE_{H_2,t} &= SOE_{H_2,t-1} + \frac{\Delta t}{60} P_{H_2,t} - D_{H_2,t} \\
 0 \leq SOE_{H_2,t} &\leq SOE_{H_2,\max} \\
 P_{H_2,t} - \alpha_{H_2,t} \cdot P_{H_2,\max} &\leq 0 \\
 P_{H_2,t} - 0.1 \cdot \alpha_{H_2,t} \cdot P_{H_2,\max} &\geq 0 \\
 S_{t+} - S_{t-} &= P_{FG,t} - P_{FG,t-1}
 \end{aligned}$$

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

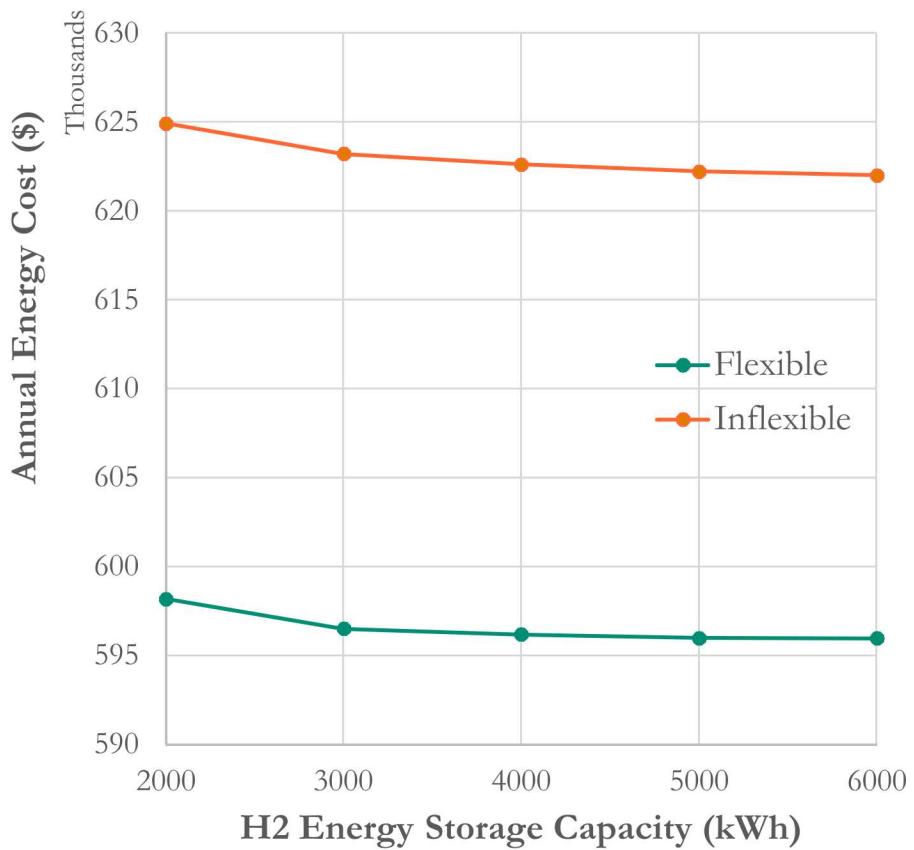
- HNEI has designed controls for flexible operation
- Sandia will assist in the implementation of site measurements and controls to realize savings
- System starting operations in early 2020

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?

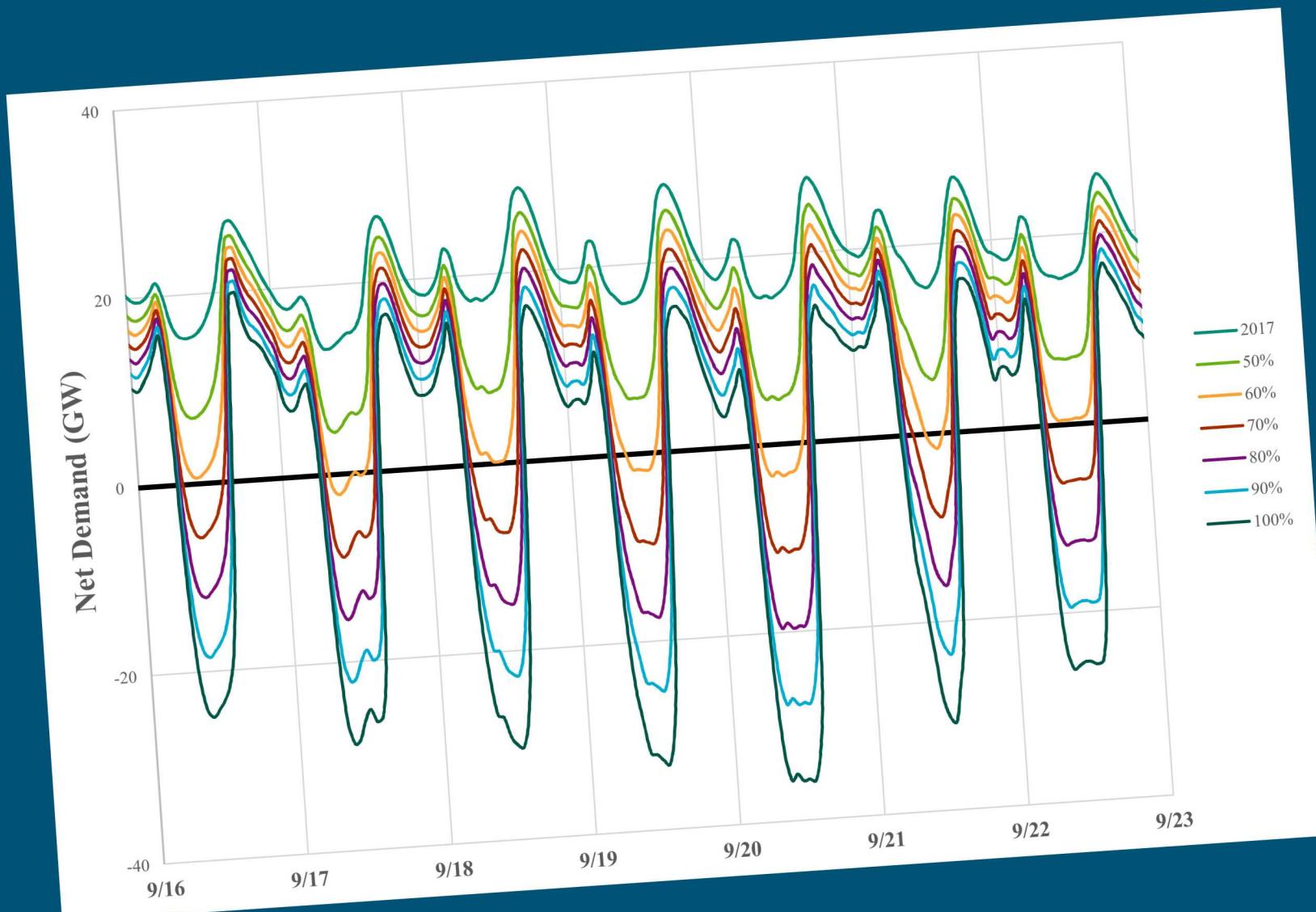


Energy Storage is a major Crosscut at the lab.

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

