

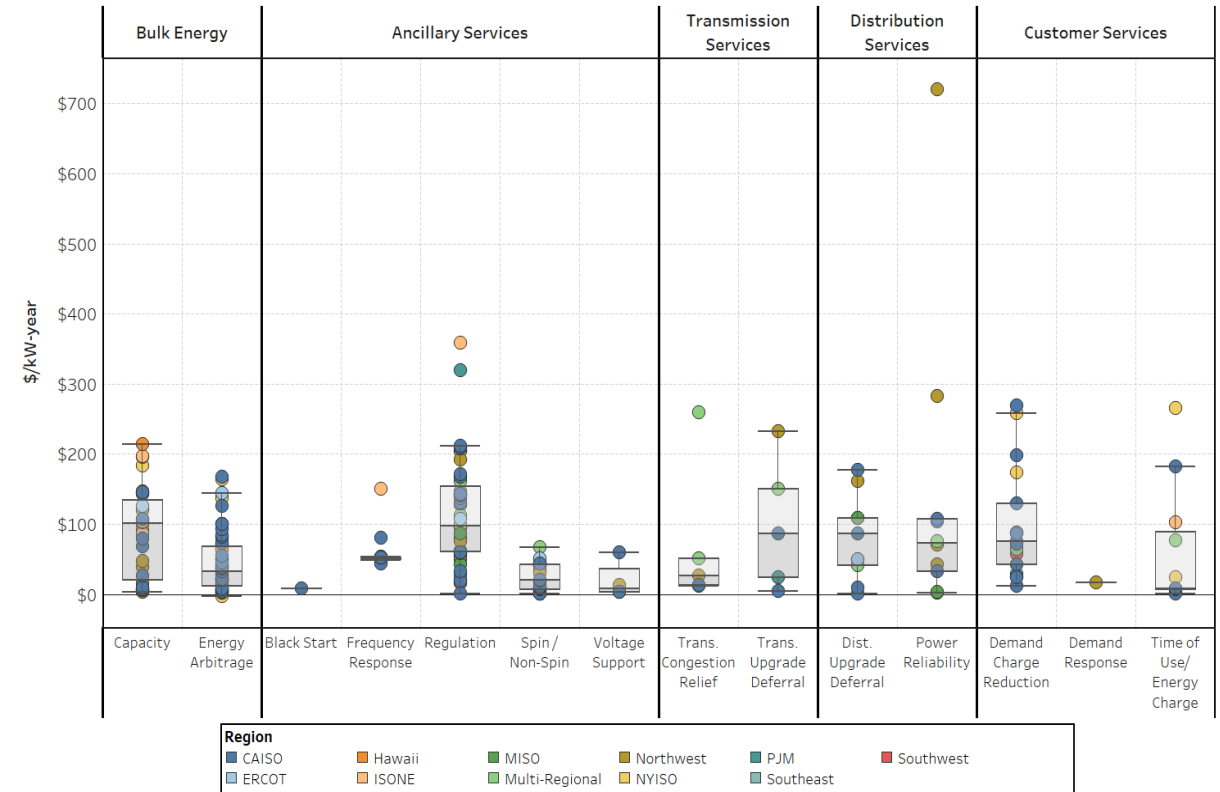
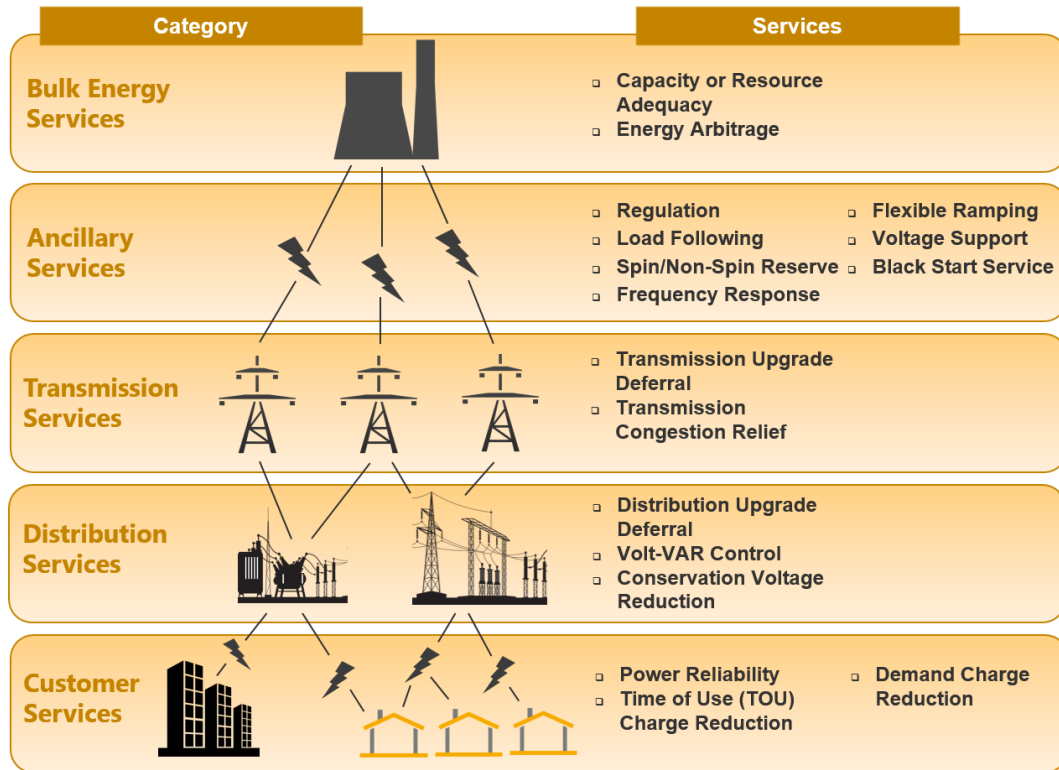
# ENERGY STORAGE VALUATION FUNDAMENTALS AND OVERVIEW OF MODELING TECHNIQUES AND TOOLS



PATRICK BALDUCCI  
Argonne National Laboratory

VERMONT PUBLIC UTILITY COMMISSION ENERGY STORAGE WEBINAR SERIES  
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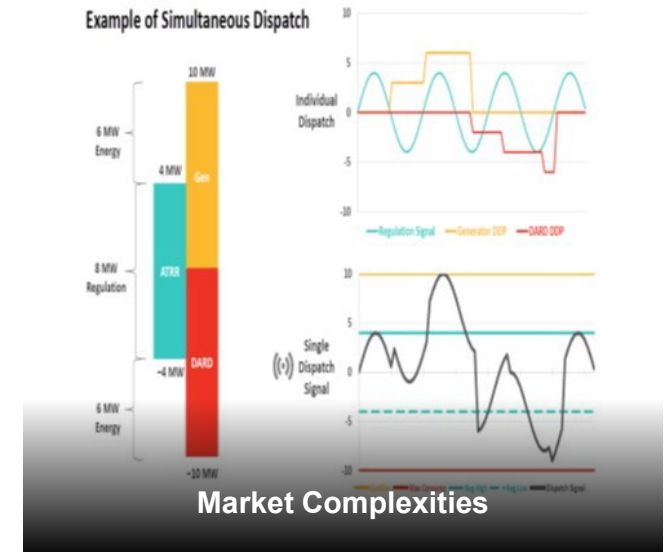
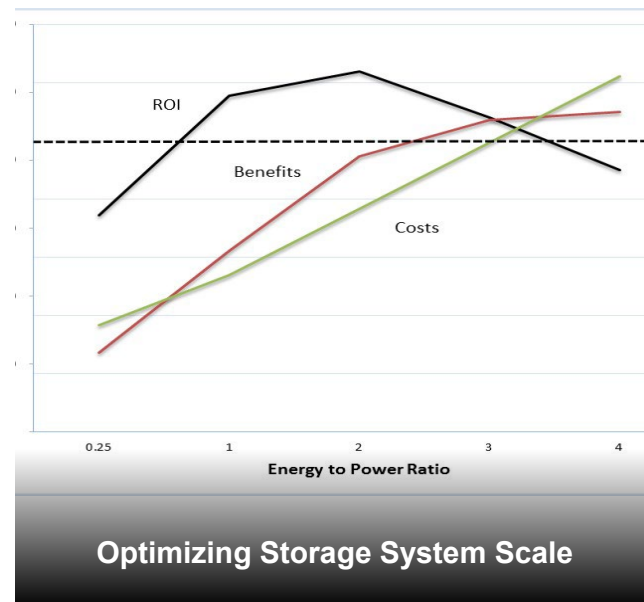
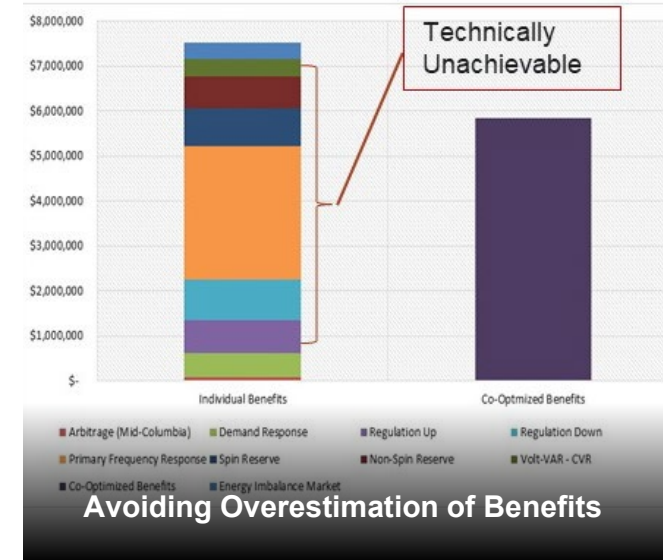
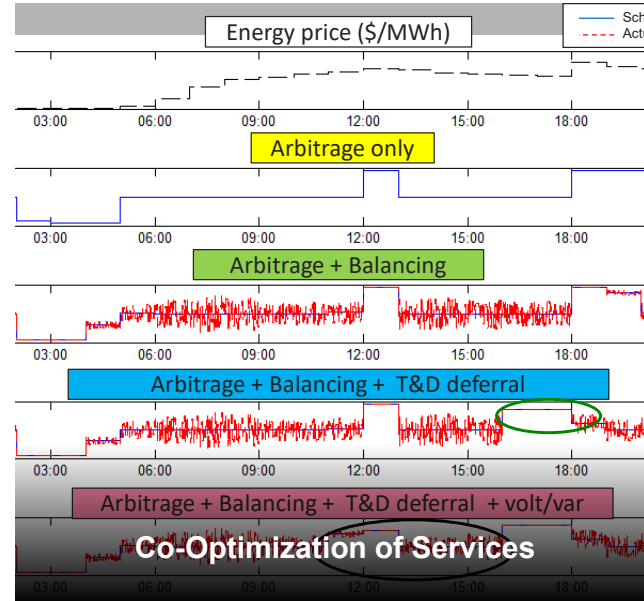
# VALUATION TAXONOMY AND META-ANALYSIS RESULTS



Source: Balducci, Patrick, Mongird, Kendall, and Weimar, Mark. *Understanding the Value of Energy Storage for Power System Reliability and Resilience Applications*. Germany: N. p., 2021. Web. <https://doi.org/10.1007/s40518-021-00183-7>.

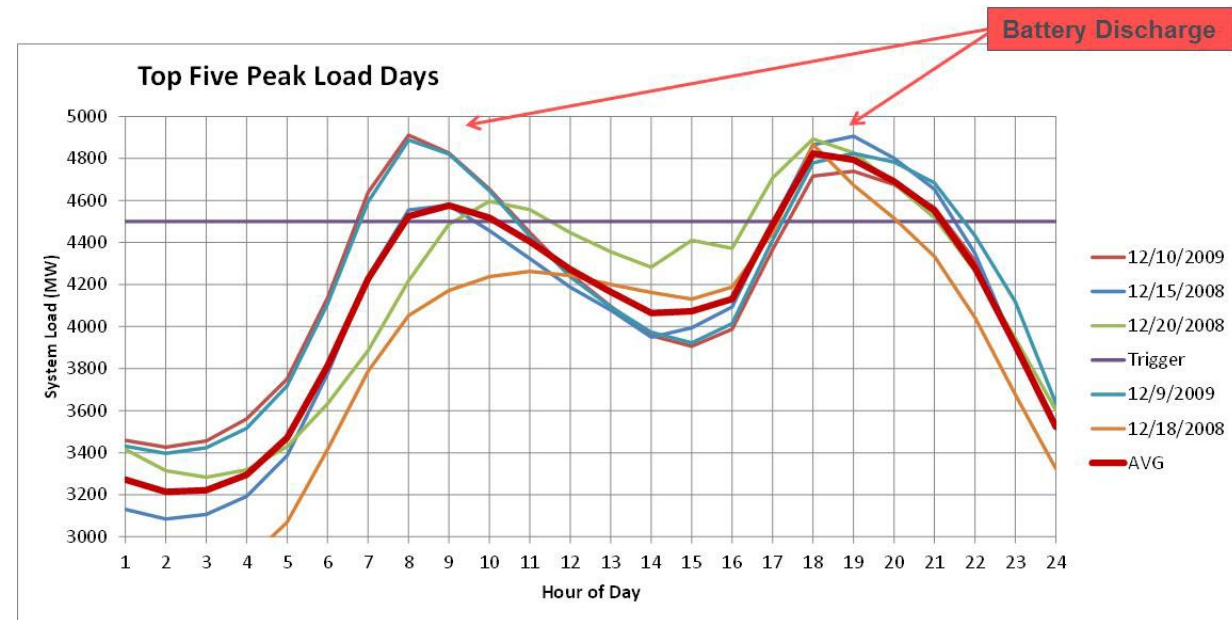
# CHALLENGES TO ACCURATELY ESTIMATING ECONOMIC BENEFITS

- Multidimensional competition for energy – not all services can be provided simultaneously and there exists intertemporal competition for energy
- Economic results are sensitive to sizing of energy storage system in terms of power and energy capacities
- Markets are complex and common practices of assuming perfect foresight into prices, price-taker position, and consistent performance lead to overestimation
- Battery performance is dynamic and there are challenges in capturing real-time value
- Battery degradation is an important consideration
- Storage valuation tools are required



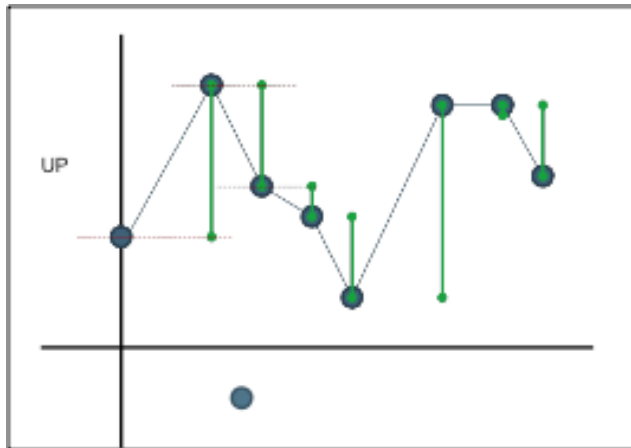
# USE CASE EXAMPLE 1: CAPACITY / RESOURCE ADEQUACY

- Capacity markets have been established in regions throughout the United States with value based on forward auction results and demonstrated asset performance
- For regulated utilities, capacity value based on the incremental cost of next best alternative investment (e.g., peaking combustion turbine) with adjustments for:
  - energy and flexibility benefits of the alternative asset, and
  - the incremental capacity equivalent of energy storage.



# USE CASE EXAMPLE 2 - FREQUENCY REGULATION

- Second-by-second adjustment in output power to maintain grid frequency
- Follow automatic generation control (AGC) signal
- Value defined by market prices or avoiding costs of operating generators



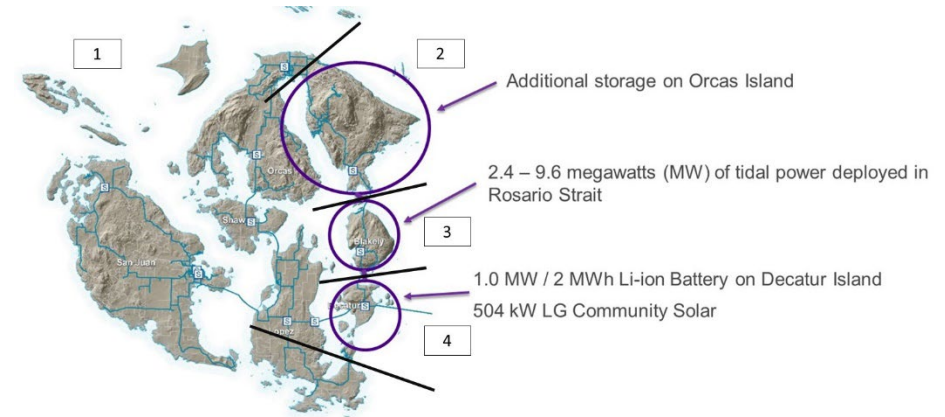
Mileage definition is the sum of all green bars in 15 min. intervals

Capacity Payment = Regulation Capacity Clearing Price  
Service Payment = Mileage (AGC Signal Basis)  
Performance = Regulation Service Performance Score

Key Lesson: Performance of battery storage in providing frequency regulation is exceptionally high. Market prices can be driven downward as a result, undermining the profit potential to storage operators in the process. Also, ancillary services markets are very shallow, limiting revenue potential.

# USE CASE EXAMPLE 3: OUTAGE MITIGATION

- Outage data
  - Outage data obtained from utility
  - Average annual number of outages determined
  - Outage start time and duration
- Customer and load information
  - Number of customers affected by outages
  - Customer outages sorted into customer classes
  - Load determined using 15-minute SCADA information
- Scenarios
  - Perfect foreknowledge
  - No foreknowledge



Orcas Power and Light Tidal, Solar plus Storage

Duration	Cost per Outage (\$2008)*		
	Residential	Small C + I	Large C + I
Momentary	\$2	\$210	\$7,331
Less than 1 hr	\$4	\$738	\$16,347
2-4 hours	\$7	\$3,236	\$40,297
8-12 hours	\$12	\$3,996	\$46,227

Source: Sullivan, M., Mercurio, M., and J. Schellenberg. 2009. "Estimated Value of Service Reliability for Electric Utility Customers in the United States." Prepared for U.S. Department of Energy by Lawrence Berkeley National Laboratory. Berkeley, CA.

Interruption Cost Estimates

# USE CASE EXAMPLE 4: TRANSMISSION AND DISTRIBUTION DEFERRAL

Key Lesson: T&D deferral values are highly site- and condition-specific.

- Energy storage used to defer investment; impact of deferral measured in present value (PV) terms
- Net present value of deferring a \$1 million investment for one year estimated at \$90,000 or \$10,400 annually over economic life of battery

$$PV = FV / (1+i)^n$$

PV = Present value

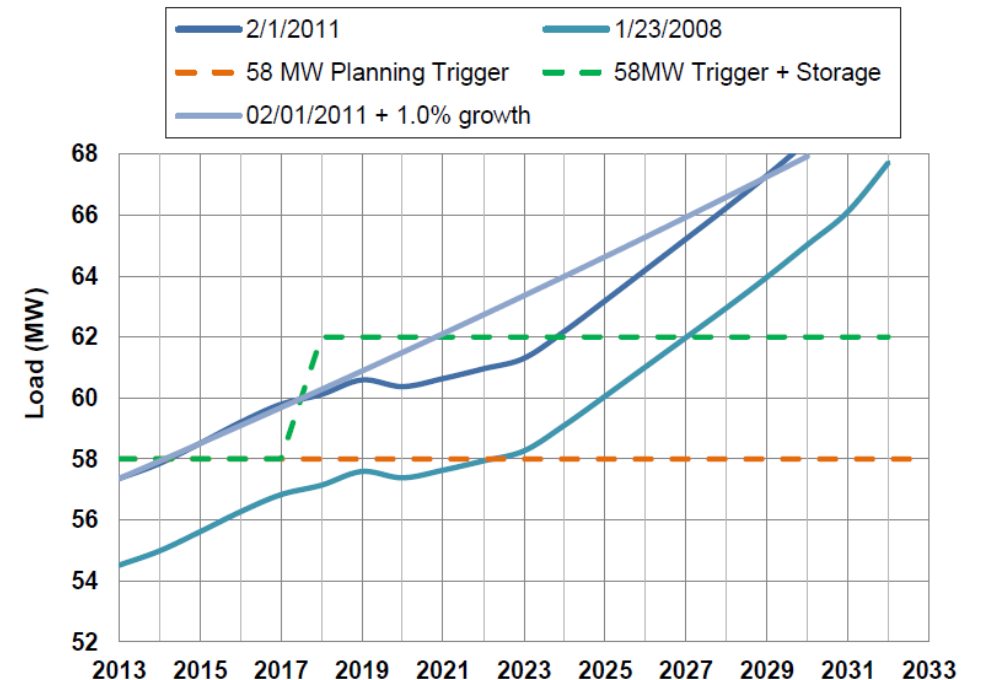
FV = Future value

i = Cost of capital

n = Number of years

*Assuming an 8% cost of capital (discount rate) and 3% cost inflation, distribution deferral of six years for a \$10 million substation would be valued at \$2.5 million based on calculation below:*

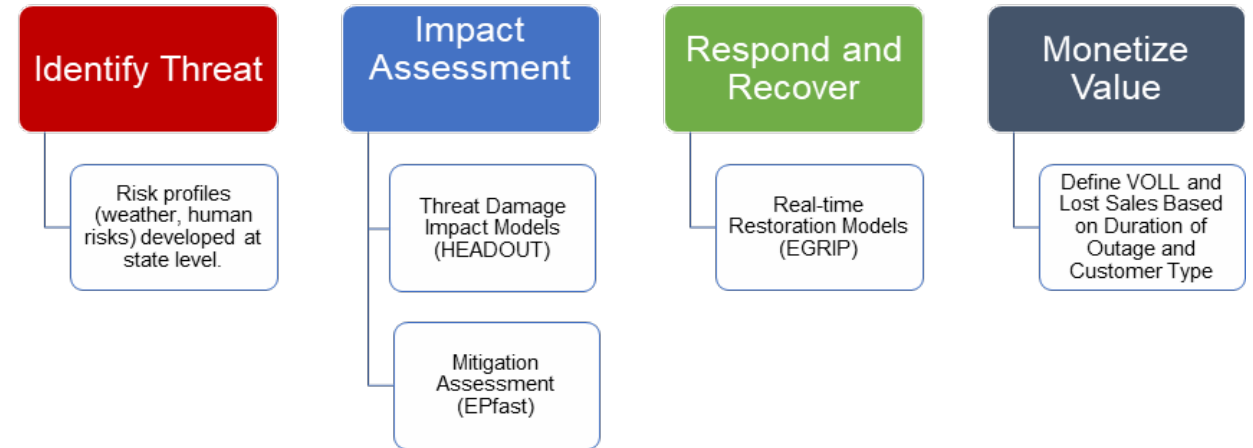
$$PV = \$10 \text{ million} * 1.03^6 / (1+.08)^6 = \$7.5 \text{ million.}$$



# VALUING RESILIENCE

Key Lesson: Resilience is rarely valued and there is no consensus on the best approach.

- Energy storage has demonstrated the capacity to enhance grid resilience
- Resilience benefits are poorly defined and generally ignored in energy storage valuation studies
- Resilience benefits are typically evaluated using customer damage functions and interruption cost studies, sometimes evaluated using willingness to pay studies (e.g., contingent valuation method) and input-output analysis
- Resilience value can be embedded in other value streams, including transmission deferral, voltage sag compensation, and outage mitigation
- We propose using multi-hazard risk analysis that relies on expected value calculations based on probabilistic analysis – annual risk premium



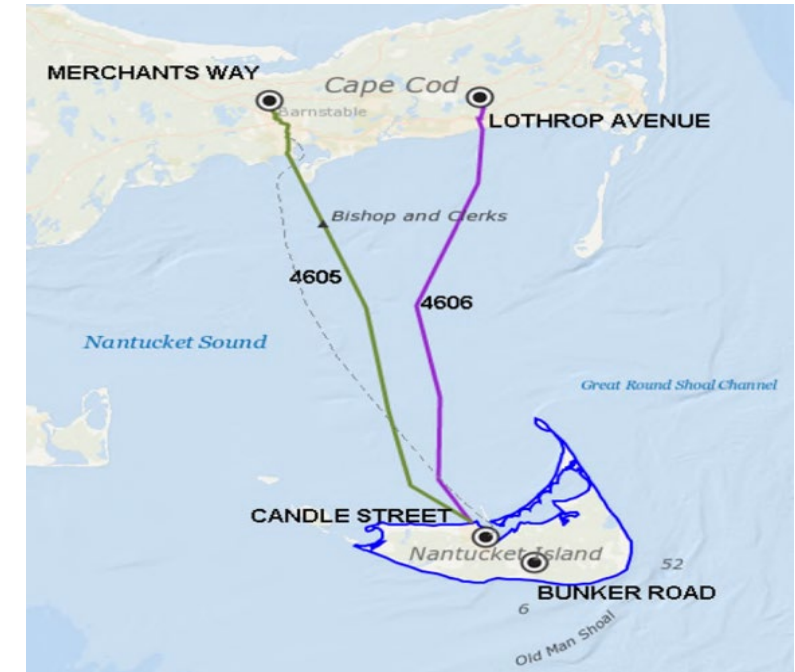
Argonne Suite of Tools for Resilience Modeling and Planning

Source: Balducci, Patrick, Mongird, Kendall, and Weimar, Mark. *Understanding the Value of Energy Storage for Power System Reliability and Resilience Applications*. Germany: N. p., 2021. Web. <https://doi.org/10.1007/s40518-021-00183-7>.



# NANTUCKET ISLAND ENERGY STORAGE SYSTEM

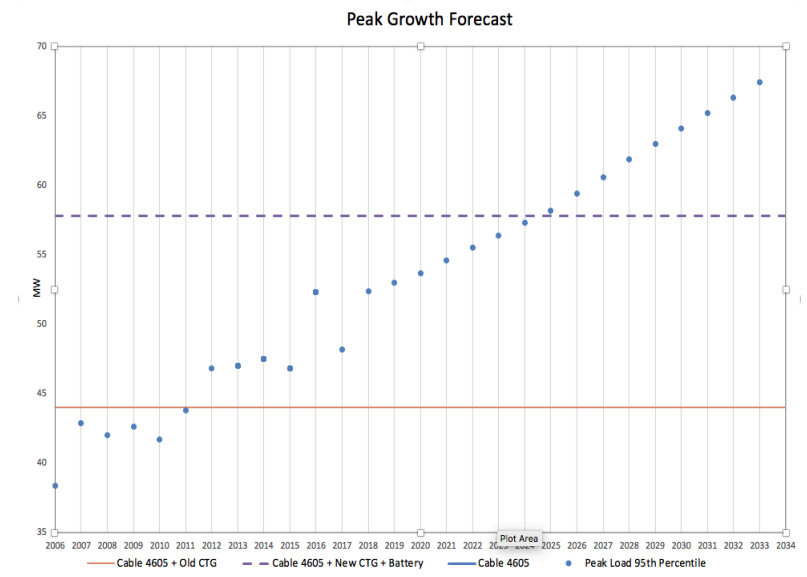
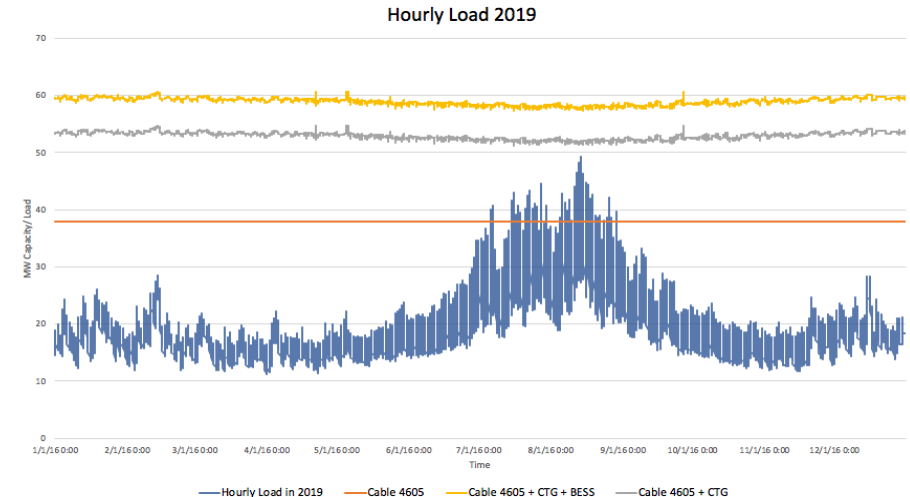
- Nantucket Island located off the coast of Massachusetts
  - Small resident population of 11,000; population swells to over 50,000 in summer
  - Nantucket's electricity supplied by two cables with a combined capacity of 71 MW and two small on-island combustion turbine generators (CTGs) with a combined capacity of 6 MW
  - Rather than deploying 3<sup>rd</sup> cable, National Grid replaced two CTGs with a single, large (16 MW) CTG and a 6 MW / 48 MWh Tesla Li-ion BESS.
- Use cases evaluated
  - Non-market operations
    - ✓ Transmission deferral
    - ✓ Outage mitigation
    - ✓ Conservation voltage reduction
    - ✓ Volt-VAR optimization
  - Market operations
    - ✓ Forward capacity market
    - ✓ Arbitrage
    - ✓ Regulation
    - ✓ Spinning reserves



Nantucket Supply Cables

# BENEFITS OF LOCAL OPERATIONS

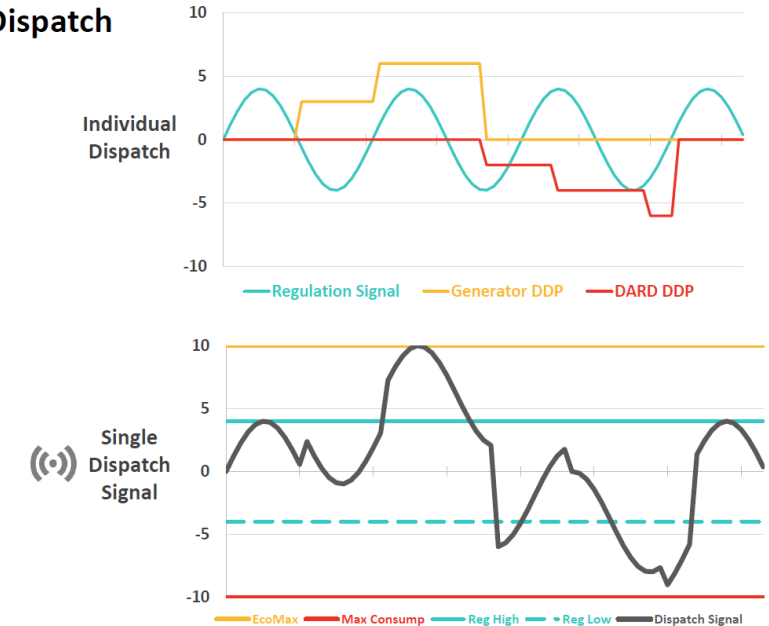
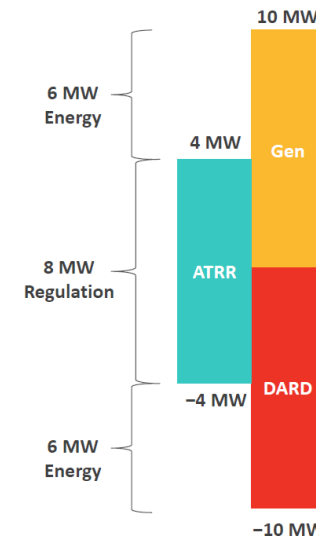
- The research team performed an extensive load analysis in order to define the n-1 contingency window and estimate the number of deferral years at 13
- Outage mitigation evaluated using historic outages and distribution system model
- Value of local operations (\$122 million) exceeds the \$93.3 million in revenue requirements for the systems, yielding an ROI ratio of 1.30



# BENEFITS OF MARKET OPERATIONS

- Nantucket BESS modeled as a continuous storage facility
- BESS bid into markets using predicted prices – i.e., imperfect foresight
- Regulation follows energy neutral AGC signal with a performance score of 95%
- Market benefits estimated at \$24.0 million over life of BESS
  - Regulation provides \$18.8 million (78%) of market benefits
  - Capacity - \$4.1 million (17%)
  - Spin reserves - \$1.2 million (5%)

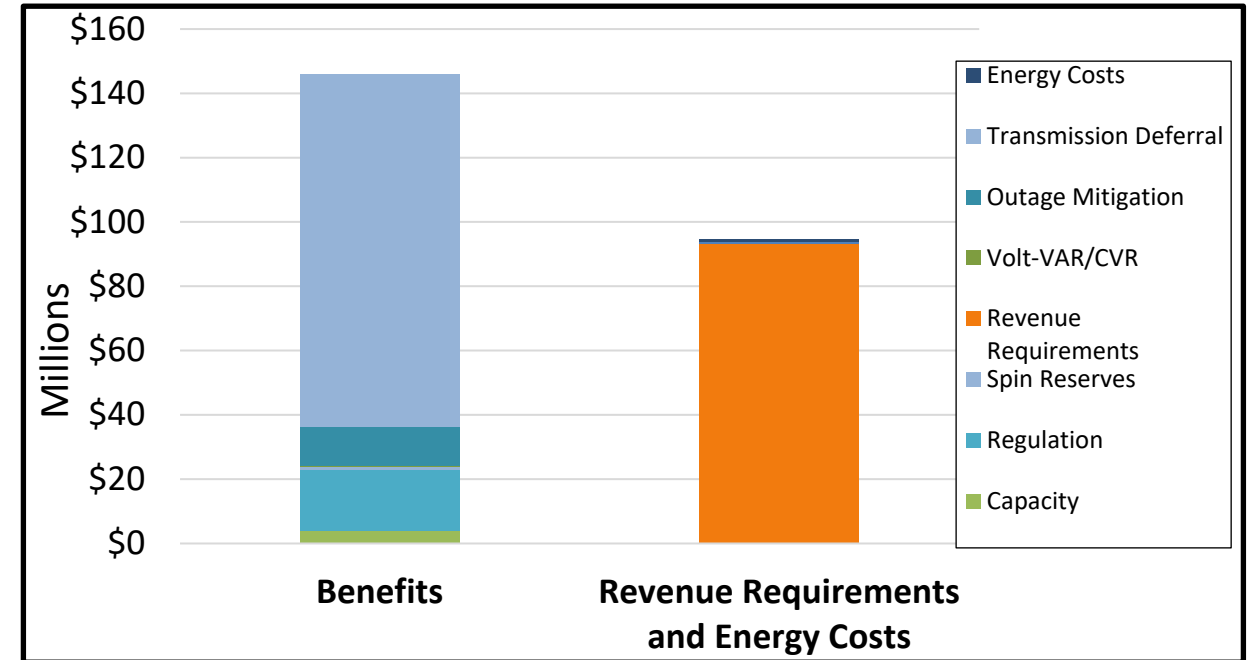
Example of Simultaneous Dispatch



Simultaneous Dispatch of Continuous Storage Facility

# NANTUCKET ISLAND CONCLUSIONS

- Total 20-year pv benefits of BESS and CTG operations at \$145.9 million exceed revenue requirements and energy costs at \$93.9 million with an ROI ratio of 1.55
- Benefits largely driven by the transmission deferral use case, \$109 million (75%) in PV terms
- Regulation services - \$18.8 million, 13% of total benefits
- Regulation service dominates the application hours, 7,900 hours each year



Benefits of Local and Market Operations (Base Case)  
vs. Revenue Requirements

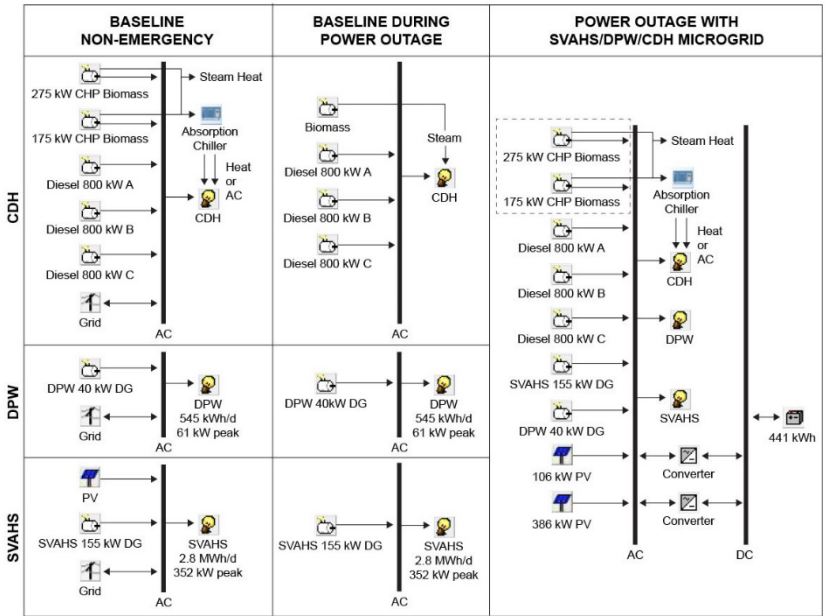
# NORTHAMPTON MICROGRID

## ■ Economic Benefits

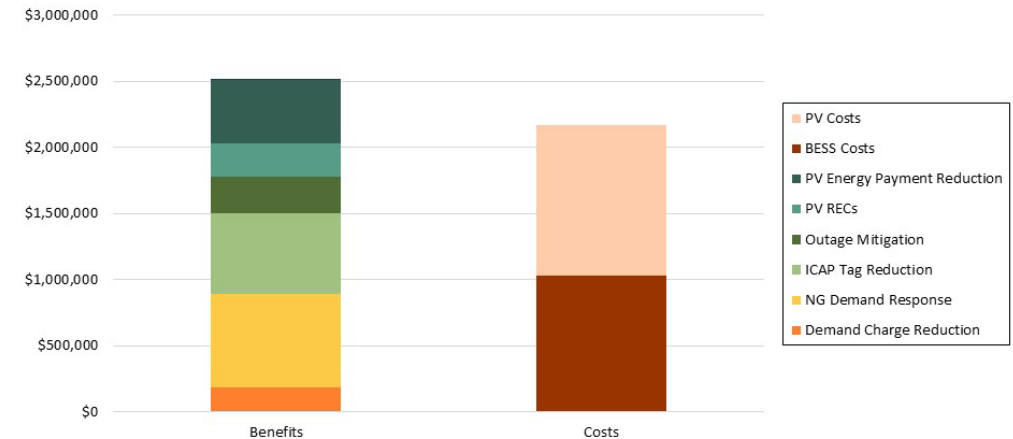
- ESS and the 386 kW solar array are estimated to generate a benefit-cost ratio of 1.16 with \$0.3 million in net benefits.

## ■ Resilience Benefits

- When there is a full microgrid and full sharing between microgrid members, all facilities are able to withstand 100% of outages up to seven days in both summer and winter. If no microgrid exists, the survivability of Smith Vocational Area High School and the Department of Public Works during a seven-day outage assuming no DG failure drops to 41.24% and 88.95%, respectively.
- When 14-day outages are considered, survivability drops significantly due to fuel shortages.



Existing and Planned Biomass Power Components of the Northampton Microgrid Project

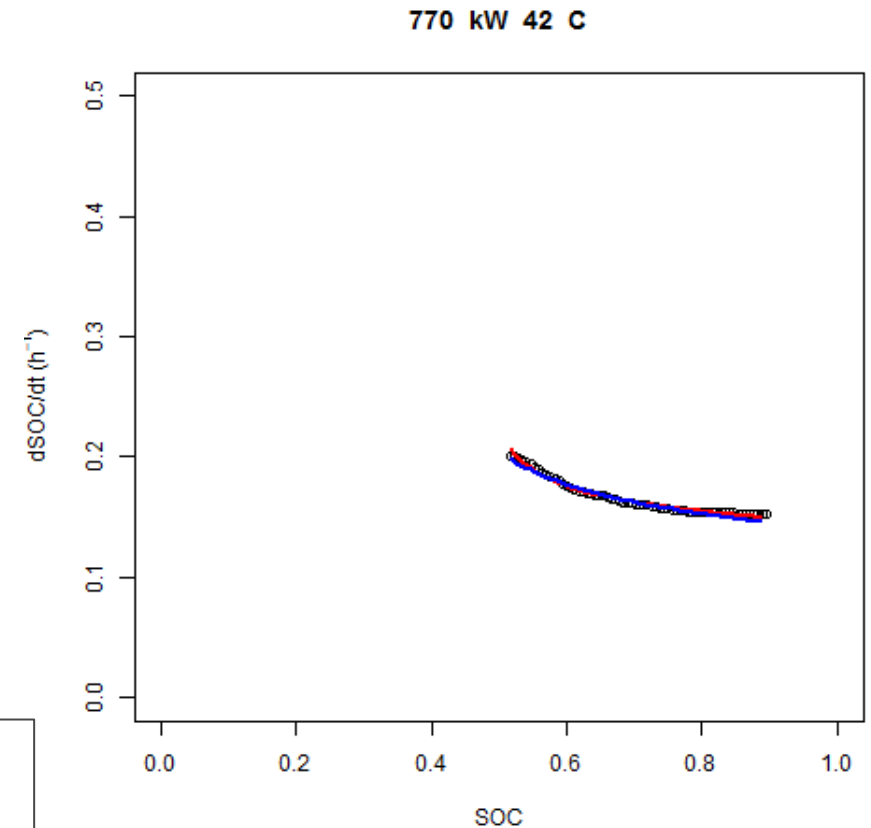


Twenty-year Benefits and Costs for the Northampton Microgrid

Source: Balducci, Patrick, Mongird, Kendall, Wu, Di, Wang, Dexin, Fotedar, Vanshika, and Dahowski, Robert. An Evaluation of the Economic and Resilience Benefits of a Microgrid in Northampton, Massachusetts. Switzerland: N. p., 2020. Web. <https://doi.org/10.3390/en13184802>

# IMPORTANCE OF OPERATIONAL KNOWLEDGE IN CAPTURING ENERGY STORAGE VALUE

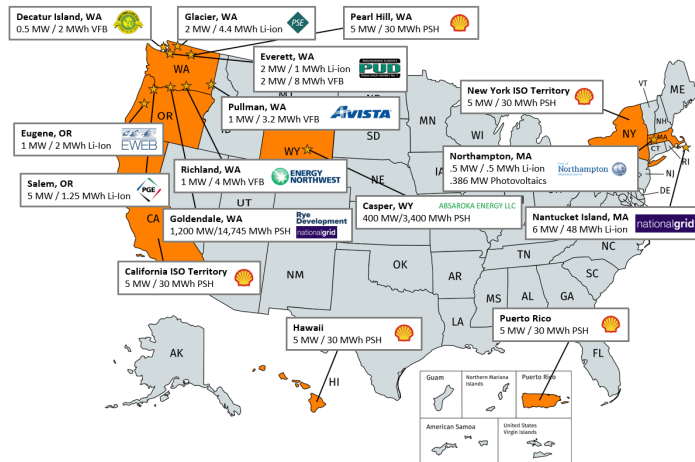
- Non-linear Performance Modeling
  - Model estimates state of charge (SOC) change during operation based on operating mode, power, SOC, and temperature
  - Model has been validated with data
  - Actual battery performance can be anticipated, thus providing a high degree of flexibility to the energy storage system owner/operator
- Co-optimizing with precise battery degradation predictions is transformational



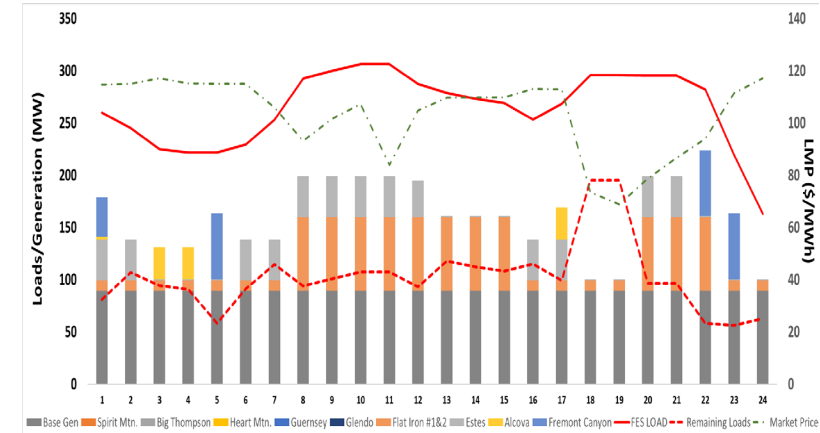
U.S. Patent No. 11,169,214, November 9, 2021, "Battery System Management through Non-Linear Estimation of Battery State of Charge"

U.S. Patent No. 10,547,180, January 28, 2020, "Battery System Management through Non-Linear Estimation of Battery State of Charge"

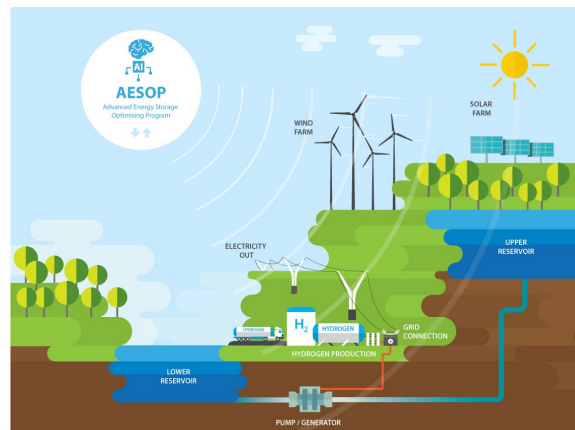
# NOVEL ENERGY STORAGE DEPLOYMENTS



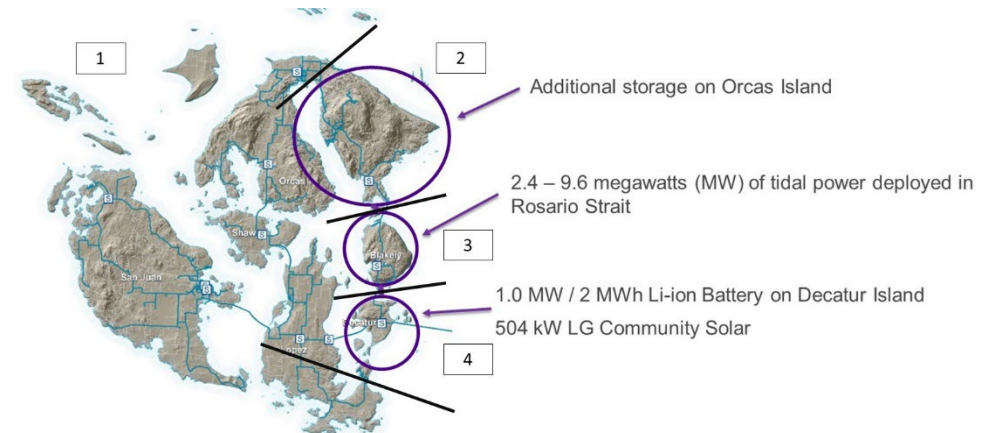
Techno-economic Assessments Led by Argonne PIs



Mt. Elbert Pumped Storage Hydro



Sunshine Hydro



Orcas Power and Light Tidal, Solar plus Storage

# ENERGY STORAGE VALUATION TOOLS

Name of Tool	Developer	Summary	Online Access
Energy Storage Evaluation Tool (ESET)	Pacific Northwest National Laboratory	ESET relies on user input time-series values and energy signals by use case to determine the optimal schedule and value of storage. It can be used for utility-owned and behind-the-meter (BTM) storage and can optimally scale the BESS.	<a href="https://availabletechnologies.pnnl.gov/technology.asp?id=413">https://availabletechnologies.pnnl.gov/technology.asp?id=413</a>
DER-VET	Electric Power Research Institute	DER-VET facilitates the understanding of where to place and install energy storage, the optimum size as well as controls options. DER-VET implements dispatch optimization with sensitivity analysis to assist in planning energy storage project development by enabling rapid analysis of scenarios with different storage sizes, costs, and value streams.	<a href="https://www.storageevet.com/">https://www.storageevet.com/</a>
QuEst	Sandia National Laboratories	QuEst is an open source, Python-based application suite for energy storage simulation and analysis. It includes market-focused and BTM tools that include detailed market prices and retail tariff rates from across the US.	<a href="https://energy.sandia.gov/tag/quest/">https://energy.sandia.gov/tag/quest/</a>
REopt Lite	National Renewable Energy Laboratory	REopt Lite is a design and analysis tool that can be used to evaluate the economic viability of grid-connected photovoltaics (PV), wind, and energy storage for BTM installations. It identifies the system sizes and battery dispatch strategy to minimize energy costs. It also estimates how long a system can sustain critical load during a grid outage.	<a href="https://reopt.nrel.gov/">https://reopt.nrel.gov/</a>



# ENERGY STORAGE USE CASES

Category	Use Case	ESET	DER-VET	QuEST	REOpt Lite
Bulk Energy	Energy Arbitrage	✓	✓	✓	✓
	Capacity	✓	✓		
Ancillary Services	Frequency Regulation	✓	✓	✓	✓
	Spin / Non-Spin	✓	✓	✓	✓
Transmission	Upgrade Deferral	✓	✓		
	Congestion Relief		✓		
Distribution	Upgrade Deferral	✓	✓		
	Volt-VAR	✓	✓		
Customer Energy Management	Power Reliability	✓	✓		✓
	TOU Charge Management	✓	✓	✓	✓
	Demand Charge Management	✓	✓	✓	✓

# ENERGY STORAGE SCHEDULING TECHNIQUES

Use Case	ESET	DER-VET	QuEst	REOpt Lite
Optimization Across All Services	✓	✓	✓	✓
Optimization for Subset of Services	✓	✓		
Heuristic or Hierarchical Dispatch		✓	✓	✓
Imperfect Foresight	✓	✓		
Optimization Horizon	Rolling 24 hour	Flexible	One Year	One Year
Optimizes Customer and Utility Use Cases Concurrently	✓	✓		✓
User Defined Scheduling (No Optimization)	✓	✓		

# WHAT WE HAVE LEARNED – NUMEROUS FACTORS DETERMINE AN ENERGY STORAGE SYSTEM'S VALUE PROPOSITION

## Siting/Sizing Energy Storage

Ability to aid in the siting of energy storage systems by capturing/measuring location-specific benefits

## Broad Set of Use Cases

Measure benefits associated with bulk energy, transmission-level, ancillary service, distribution-level, and customer benefits at sub-hourly level

## Regional Variation

Differentiate benefits by region and market structures/rules

## Utility Structure

Define benefits for different types of utilities (e.g., co-ops, utilities in organized markets, and vertically integrated investor-owned utilities operating in regulated markets)

## Battery Characteristics

Accurately characterize battery performance, including round trip efficiency rates across varying SOCs and battery degradation caused by cycling

# ACKNOWLEDGMENTS

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Giovanni Damato, Electric Power Research Institute

Kate Anderson, National Renewable Energy Laboratory

Di Wu, Pacific Northwest National Laboratory



*Mission – to ensure a resilient, reliable, and flexible electricity system through research, partnerships, facilitation, modeling and analytics, and emergency preparedness.*

<https://www.energy.gov/oe/activities/technology-development/energy-storage>

# CONTACT INFORMATION

**Patrick Balducci**

**[pbalducci@anl.gov](mailto:pbalducci@anl.gov)**

**503-679-7316**



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