

# INTRODUCTION TO ENERGY STORAGE ECONOMICS



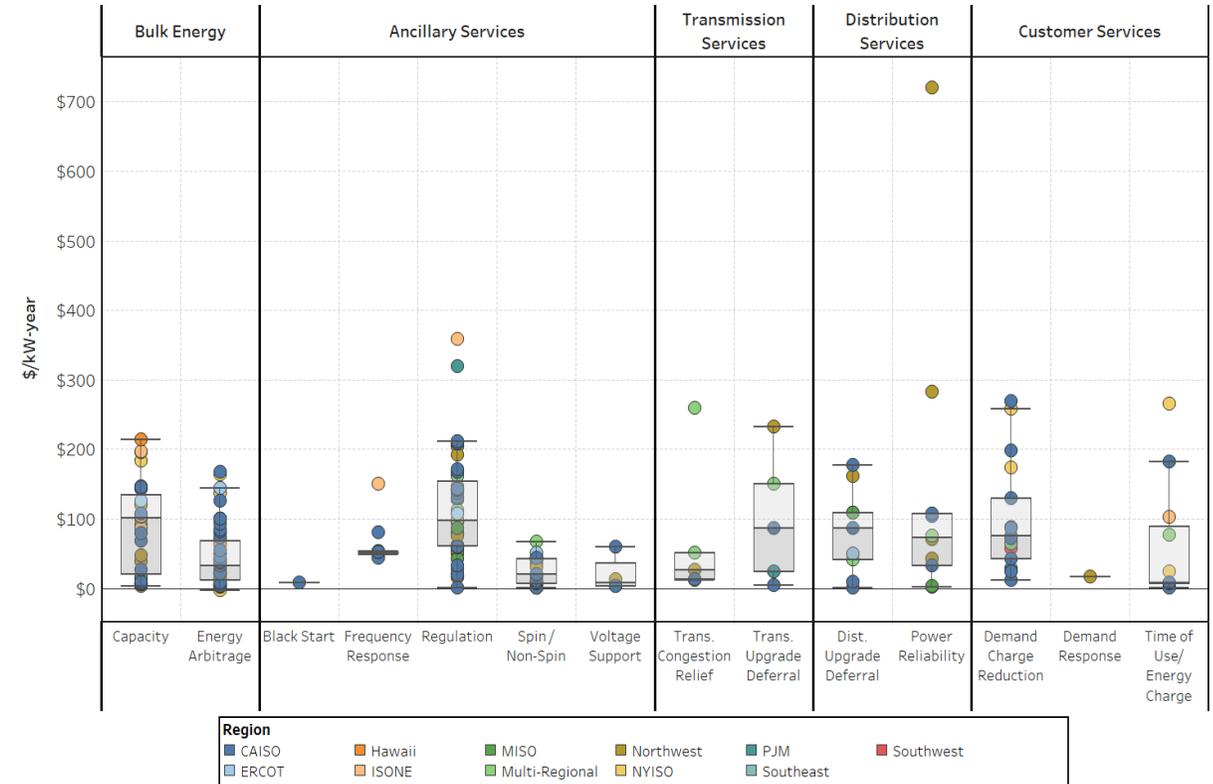
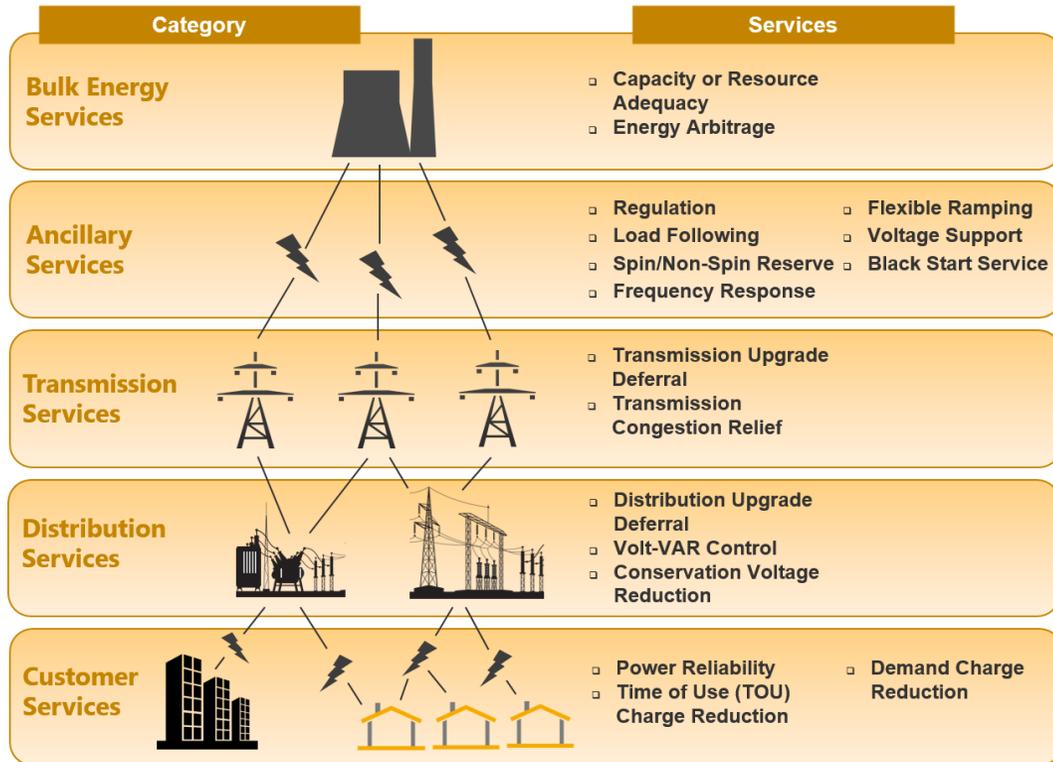
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**WASHINGTON DC DEPARTMENT OF ENERGY & ENVIRONMENT ENERGY STORAGE WEBINAR SERIES:  
SESSION 1 – INTRODUCTION TO ENERGY STORAGE**

**OCTOBER 26, 2022**

# 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>.

# USE CASE EXAMPLE 1: CAPACITY / RESOURCE ADEQUACY

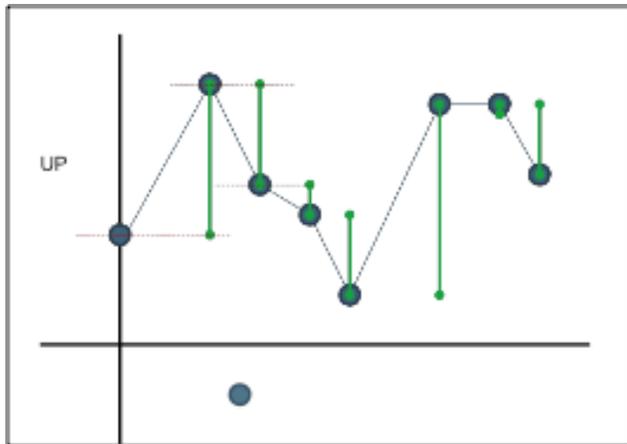
- Capacity markets have been established in regions throughout the United States with value based on forward auction results and demonstrated asset performance
- For regulated utilities, capacity value based on the incremental cost of next best alternative investment (e.g., peaking combustion turbine)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

ISO/RTO	Subregion	Delivery Year				
		2021	2022	2023	2024	2025
ISO-NE	Northern	\$55.56/kW-year	\$45.60/kW-year	\$24.00/kW-year	\$29.76/kW-year	\$30.37/kW-year
	Southeast	\$55.56/kW-year	\$45.60/kW-year	\$24.00/kW-year	\$47.76/kW-year	\$31.67/kW-year
	Rest of Pool	\$55.56/kW-year	\$45.60/kW-year	\$24.00/kW-year	\$31.32/kW-year	\$31.09/kW-year
MISO	North (Zones 1-7)	\$1.83/kW-year	\$86.38/kW-year			
	South (Zones 8-10)	\$0.00/kW-year	\$1.05/kW-year			
NYISO	Zones G-J	\$33.42/kW-year	\$67.92/kW-year			
	Long Island (LI)	\$41.04/kW-year	\$58.56/kW-year			
	New York City (NYC)	\$42.00/kW-year	\$79.44/kW-year			
	New York Control Area (NYCA)	\$30.54/kW-year	\$52.80/kW-year			
PJM	Mid-Atlantic Area Council (MAAC)	\$60.49/kW-year	\$34.96/kW-year	\$18.06/kW-year		
		\$73.11/kW-year	\$35.72/kW-year	\$25.53/kW-year		
		\$74.57/kW-year	\$46.17/kW-year			
	Other	\$51.10/kW-year	\$18.25/kW-year	\$12.46/kW-year		
		\$62.54/kW-year	\$25.17/kW-year			
		\$71.38/kW-year	\$26.17/kW-year			

Results from Recent Forward Capacity Market Auctions Across U.S.

# 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



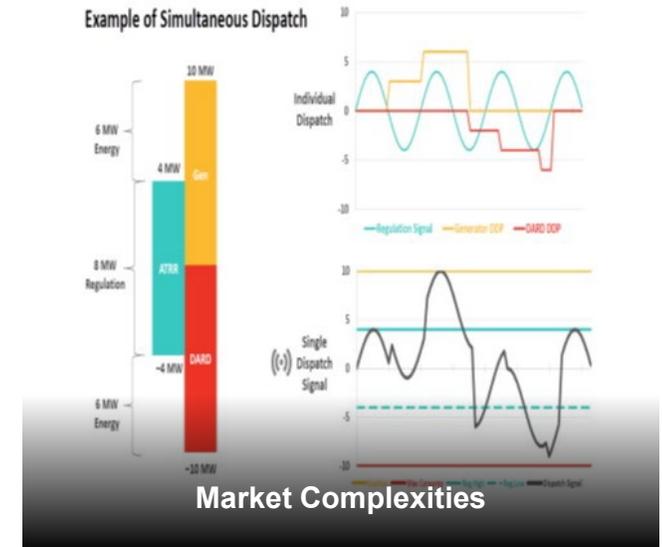
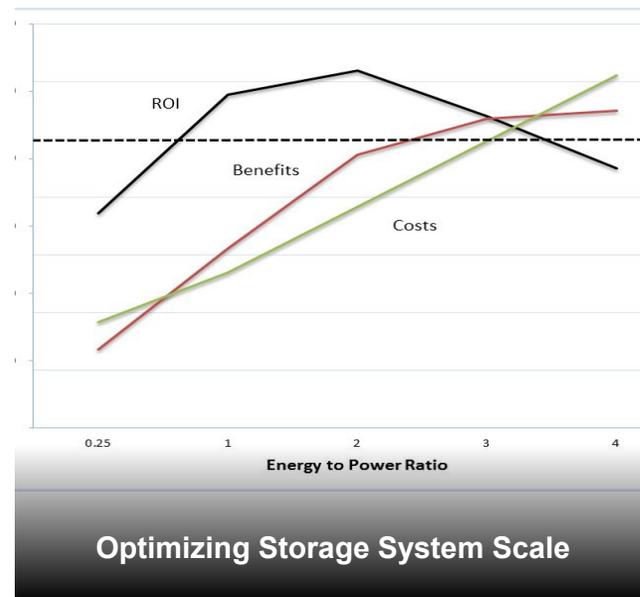
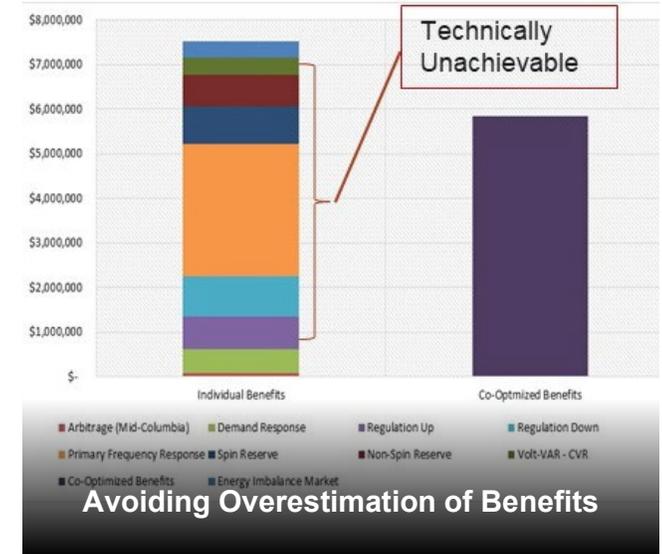
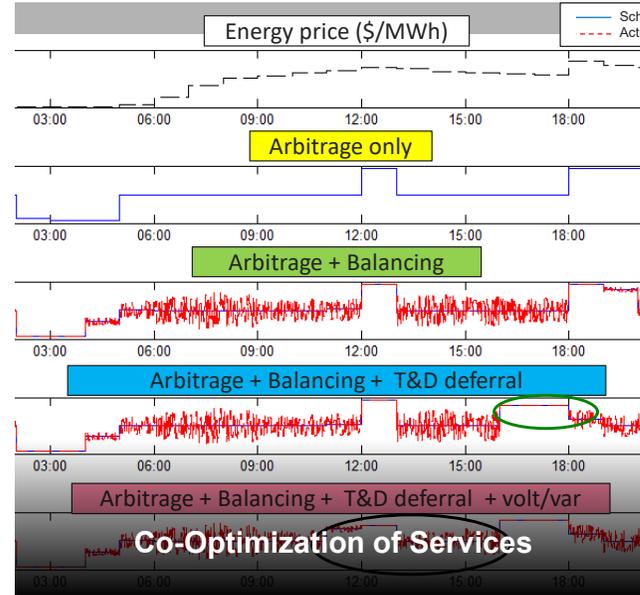
Mileage definition is the sum of all green bars in 15 min. intervals

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 and frequency regulation markets are very shallow (i.e., 1% of peak load in market). Market prices can be driven downward as a result, undermining the profit potential to storage operators in the process.

# 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
- Advanced storage valuation tools are required



# ENERGY STORAGE VALUATION TOOLS

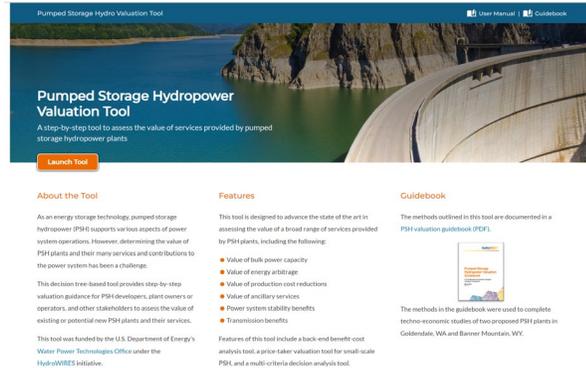
Name of Tool	Developer	Summary	Online Access
Energy Storage Evaluation Tool (ESET)	Pacific Northwest National Laboratory	ESET relies on user input time-series values and energy signals by use case to determine the optimal schedule and value of storage. It can be used for utility-owned and behind-the-meter (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 VALUATION TOOLS – KEY CHARACTERISTICS

Category	Use Case	ESET	DER-VET	QuEst	REOpt Lite
<b>Use Cases</b>					
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	✓	✓	✓	✓
<b>Energy Storage Scheduling Techniques</b>					
Optimization Across All Services		✓	✓	✓	✓
Price Impacts		Price-taker	Price-taker	Price-taker	Price-taker
Imperfect Foresight		✓	✓		
Optimization Horizon		Rolling 24 hour Over 1 Year	Flexible; Can Cover Economic Life of Storage	One Year	One Year
Optimizes Customer and Utility Use Cases Concurrently		✓	✓		✓

# ARGONNE STORAGE VALUATION TOOLS

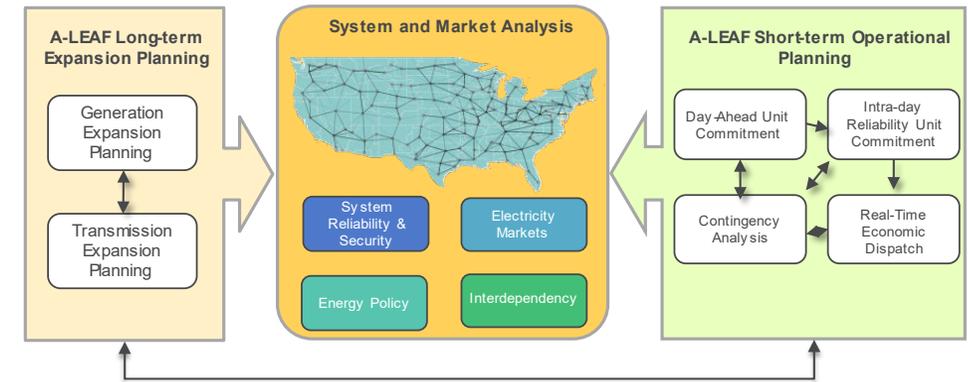
## PSH Valuation Tool (PSHVT)



PSHVT Home Page

- PSHVT enables valuation from a system, plant operator, or societal perspective
- Use case coverage includes bulk energy, ancillary, transmission, behind-the-meter, and reliability services
- PSHVT has several advanced features: a) embedded price-taker model, b) multi-criteria decision analysis tool, c) embedded financial worksheets and benefit-cost analysis model, and d) A-LEAF system model
- Access tool at <https://pshvt.egs.anl.gov>

## LDES Analysis Using A-LEAF

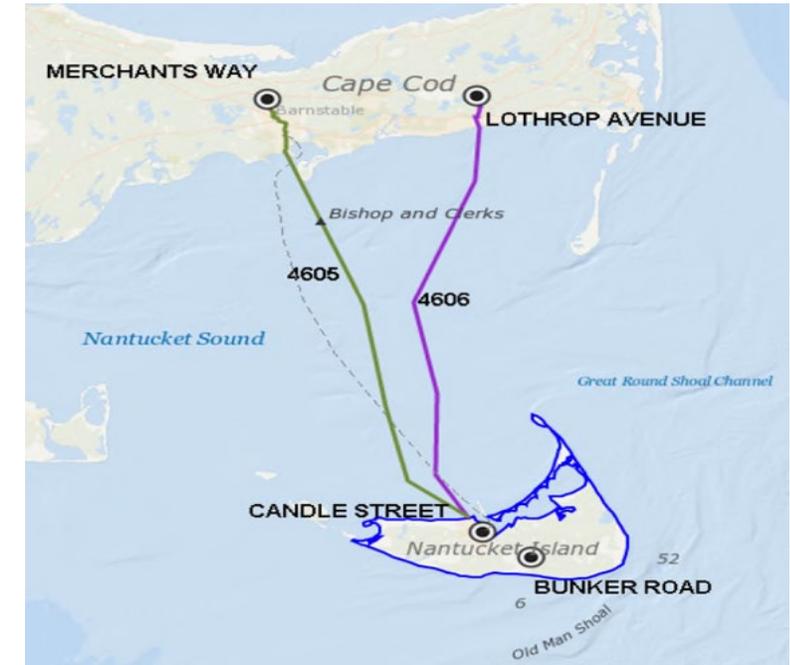


Argonne Least-Cost Electricity Framework

- Integrated national-scale power system simulation framework developed at Argonne, used to analyze issues related to the evolution of the nation's power system
- Suite of least-cost generation & transmission expansion, unit commitment, and economic dispatch models
- Determine optimal generation portfolio and hourly or sub-hourly unit dispatch under a range of user-defined input assumptions for technology characteristics and system/market requirements

# NANTUCKET ISLAND ENERGY STORAGE SYSTEM

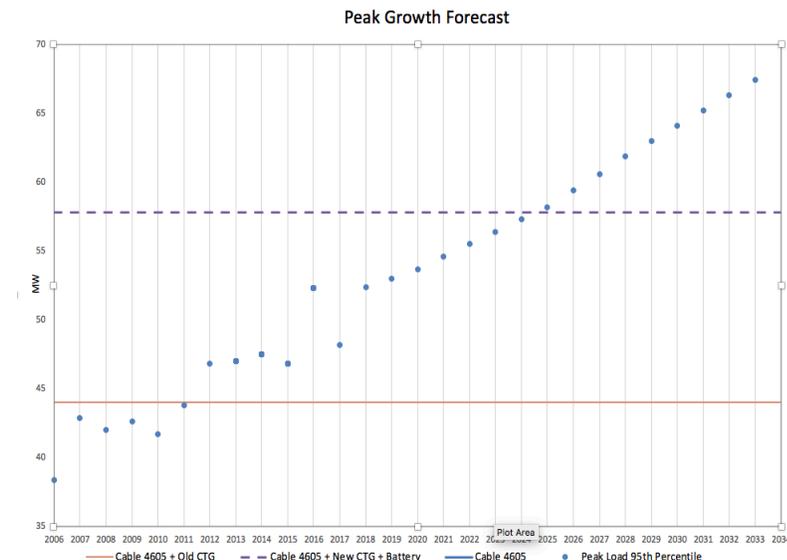
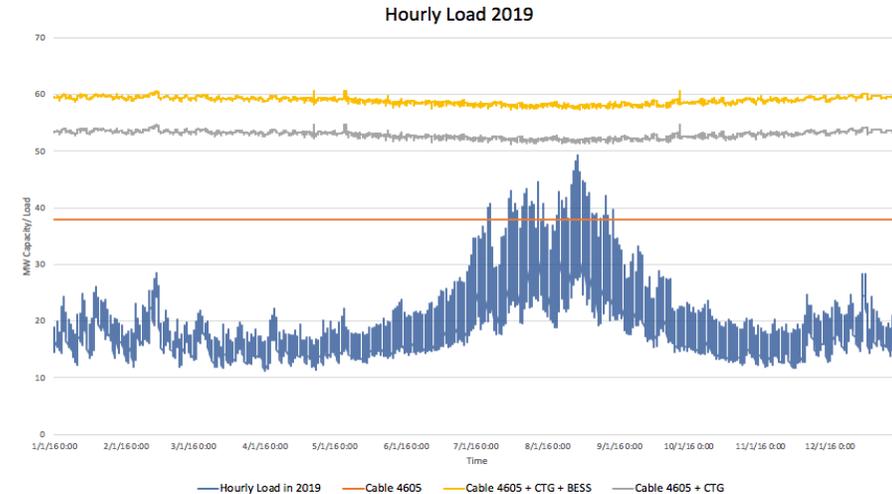
- Nantucket Island located off the coast of Massachusetts
  - Small resident population of 11,000; population swells to over 50,000 in summer
  - Nantucket's electricity supplied by two cables with a combined capacity of 71 MW and two small on-island combustion turbine generators (CTGs) with a combined capacity of 6 MW
  - Rather than deploying 3<sup>rd</sup> cable, National Grid is replacing 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

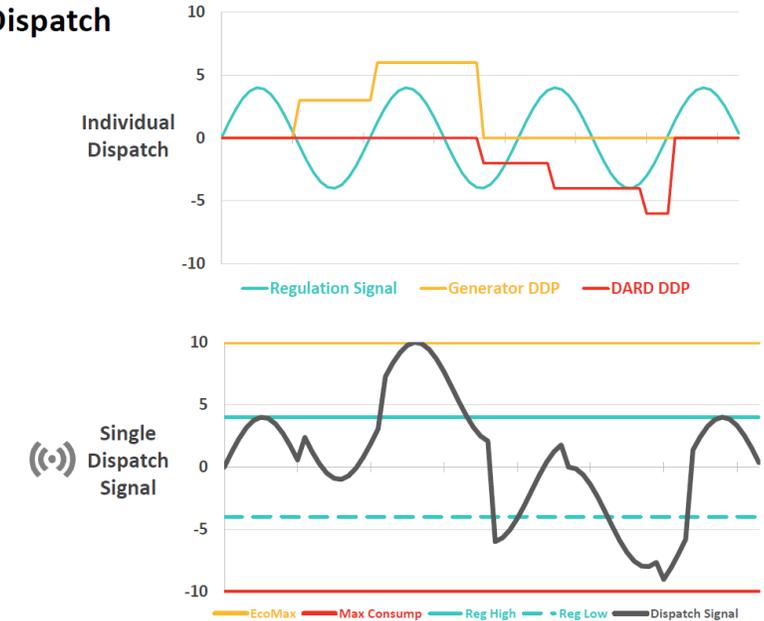
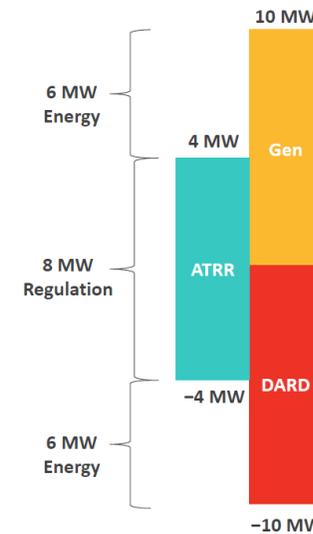
- The research team performed an extensive load analysis in order to define the n-1 contingency window and estimate the number of deferral years at 13
- Outage mitigation evaluated using historic outages and distribution system model
- Value of local operations (\$122 million) exceeds the \$93.3 million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

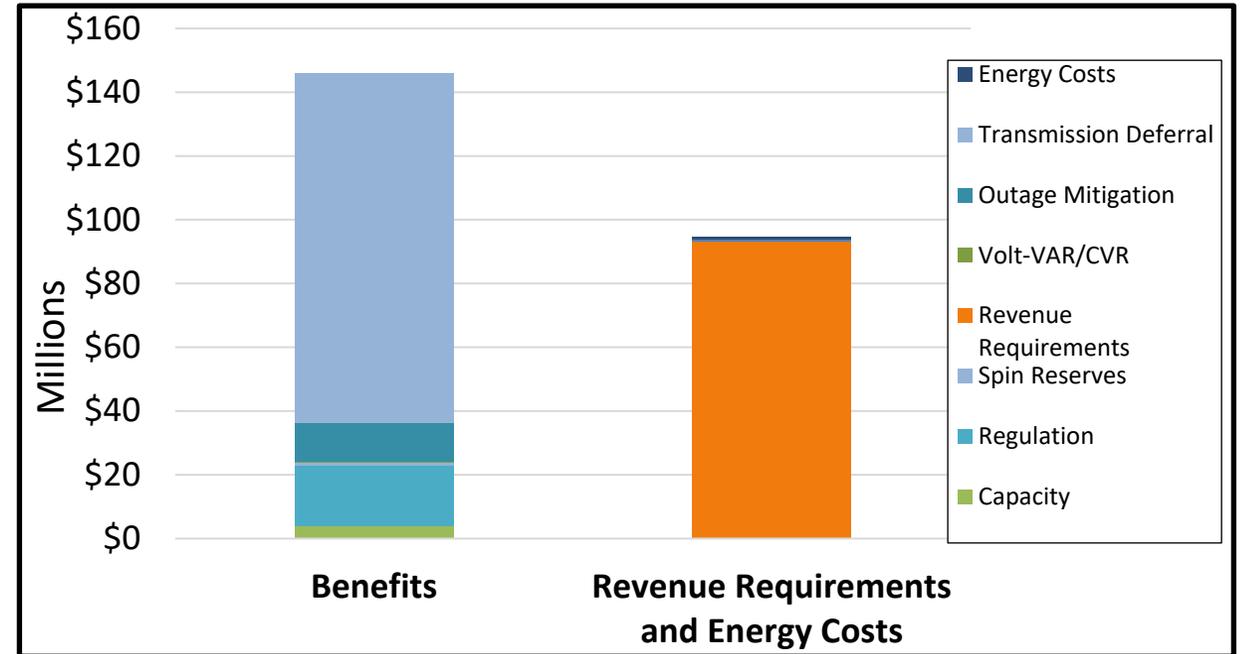
Example of Simultaneous Dispatch



Simultaneous Dispatch of Continuous Storage Facility

# NANTUCKET ISLAND CONCLUSIONS

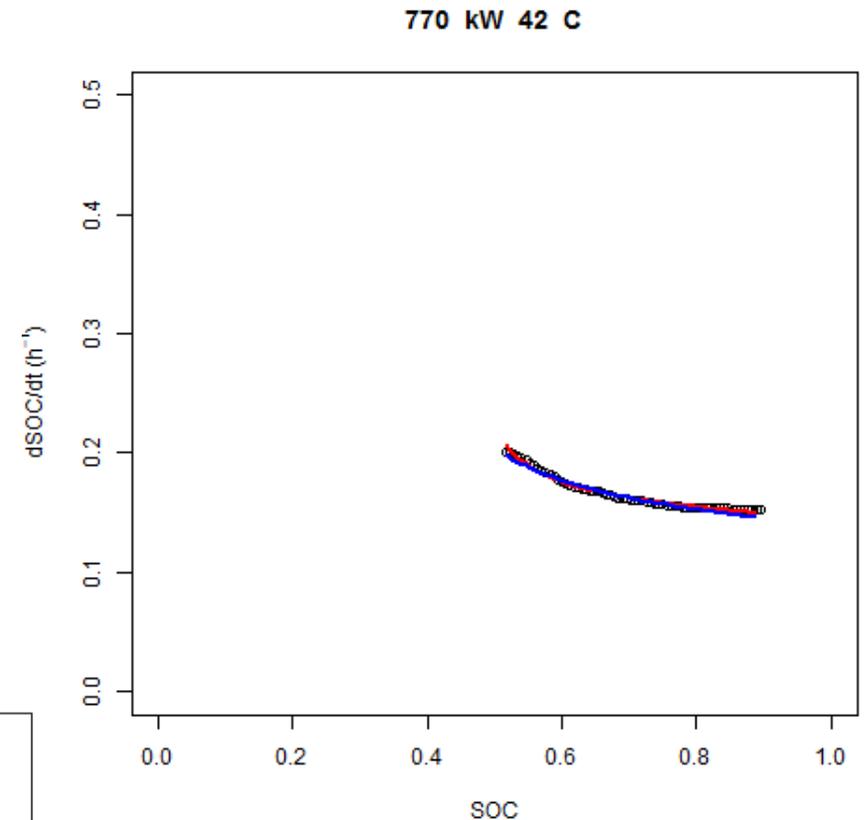
- Total 20-year pv benefits of BESS and CTG operations at \$145.9 million exceed revenue requirements and energy costs at \$93.9 million with an ROI ratio of 1.55
- Benefits largely driven by the transmission deferral use case, \$109 million (75%) in PV terms
- Regulation services - \$18.8 million, 13%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

# 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
- Self-learning model applicable to any type of storage system

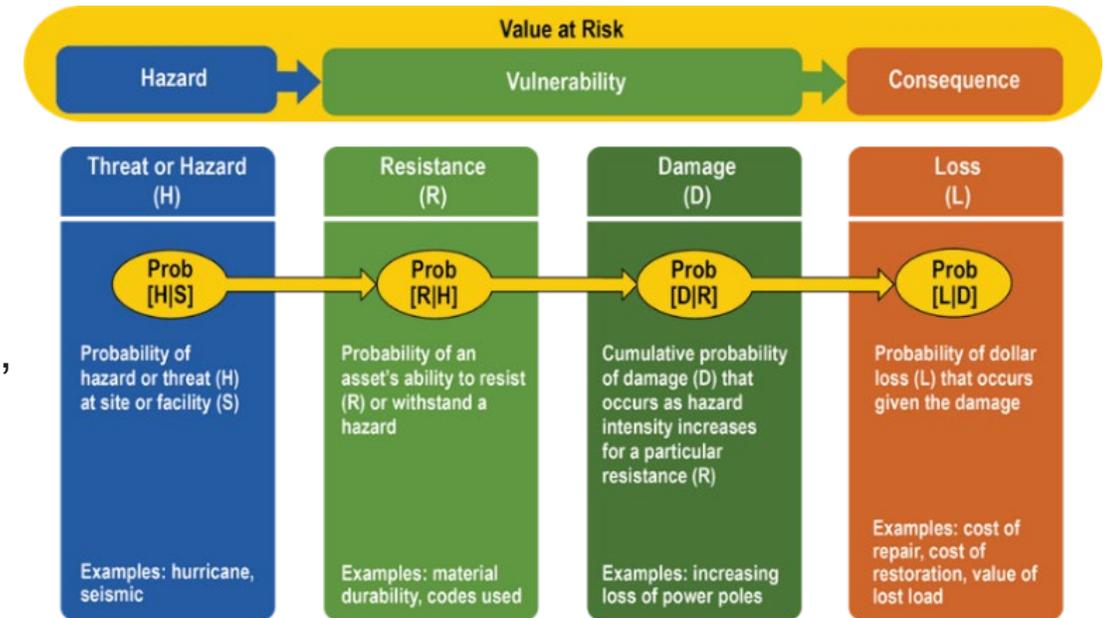


U.S. Patent No. 11,169,214, November 9, 2021, "Battery System Management through Non-Linear Estimation of Battery State of Charge"

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

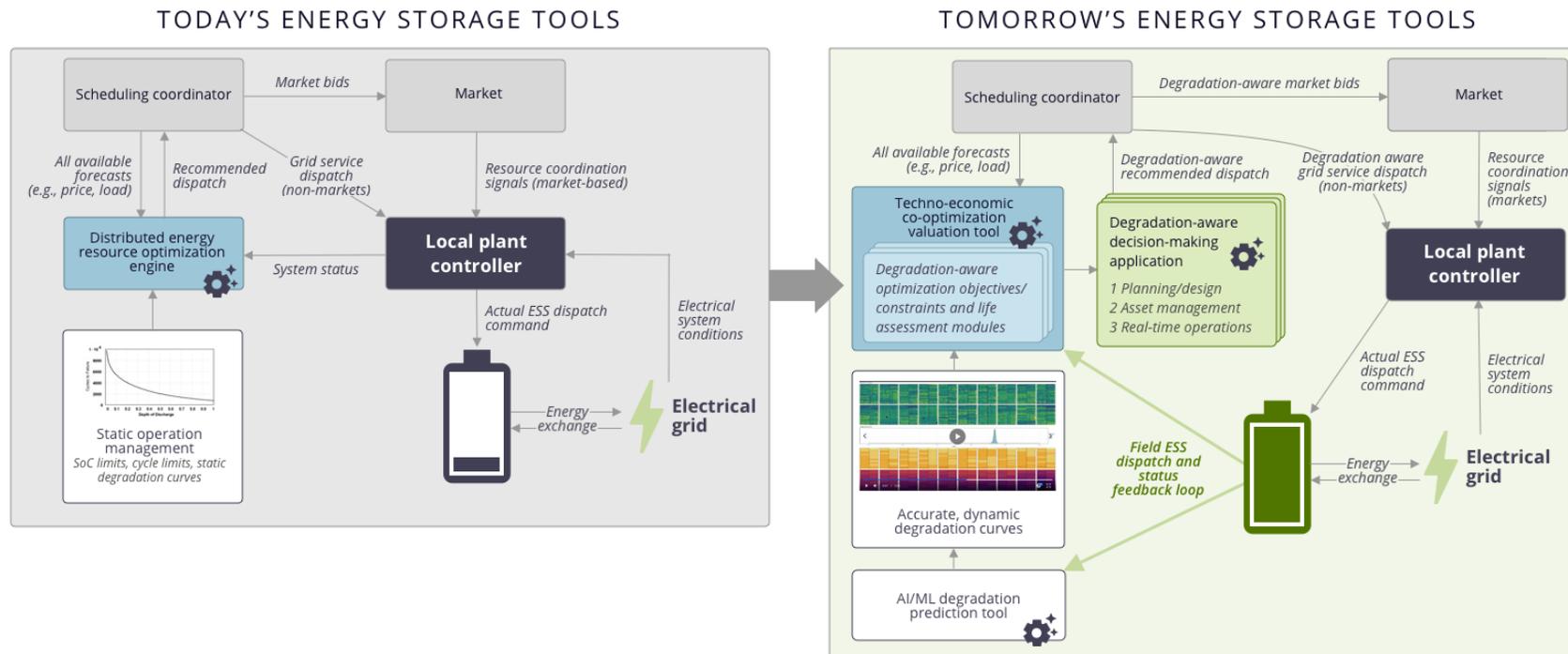
# VALUING RESILIENCE

- 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
- Multi-hazard risk analysis that relies on expected value calculations based on probabilistic analysis, while addressing a broad range of hazards and values tied to lost economic productivity, infrastructure damage, and injuries/fatalities is required – annual risk premium approach
- More research is needed to properly value resilience



Pictorial Approach to Value Risk Assessment and Resilience Valuation

# CO-OPTIMIZING WITH PRECISE BATTERY DEGRADATION PREDICTIONS IS TRANSFORMATIONAL



- ES operating life can appear in terms of a series of budgets for various cycles characterized by depth of discharge, temperature, power output, and other factors.
- Degradation-aware design/planning, asset management tools, and control systems required to allocate cycles more efficiently and expand number of cycles.
- AI degradation prediction communicates battery health estimation/prediction through degradation curves/penalties to enhance operational efficiency.

# KEY ANALYTICAL NEEDS

## Advanced Storage Valuation Tools

Models that consider a broad set of use cases, capture regional differences in benefits, and add realism to valuation process

## Risk and Uncertainty

Important to capture key risk and uncertainty associated with imperfect foreknowledge of prices, price influencing behavior, climate uncertainty; need for stochastic optimization

## Battery Characteristics

Accurately characterize battery performance, including round trip efficiency rates across varying SOC and battery degradation caused by cycling; end-of-life management

## Reliability

There are numerous reliability services (e.g., voltage support, primary frequency response, transient stability, small-signal stability) that are challenging to quantify and are rarely monetized

## Cross-sectoral Modeling

With the goal of deep decarbonization top-of-mind, system of system models that consider multiple sectors and energy transport systems are required

# ACKNOWLEDGMENTS

**Dr. Imre Gyuk, DOE – Office of Electricity**



*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

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