INTRODUCTION TO ENERGY STORAGE ECONOMICS

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ICC/SNL/DOE ENERGY STORAGE WEBINAR SERIES: SESSION 1 – INTRODUCTION TO ENERGY STORAGE
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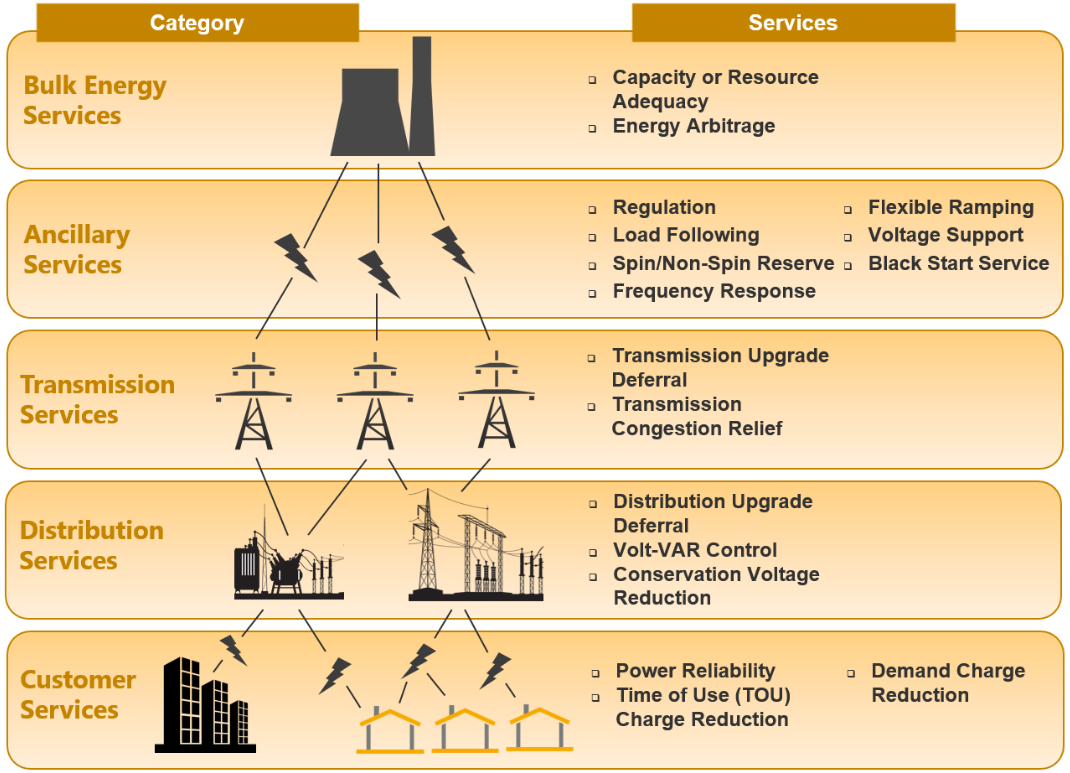
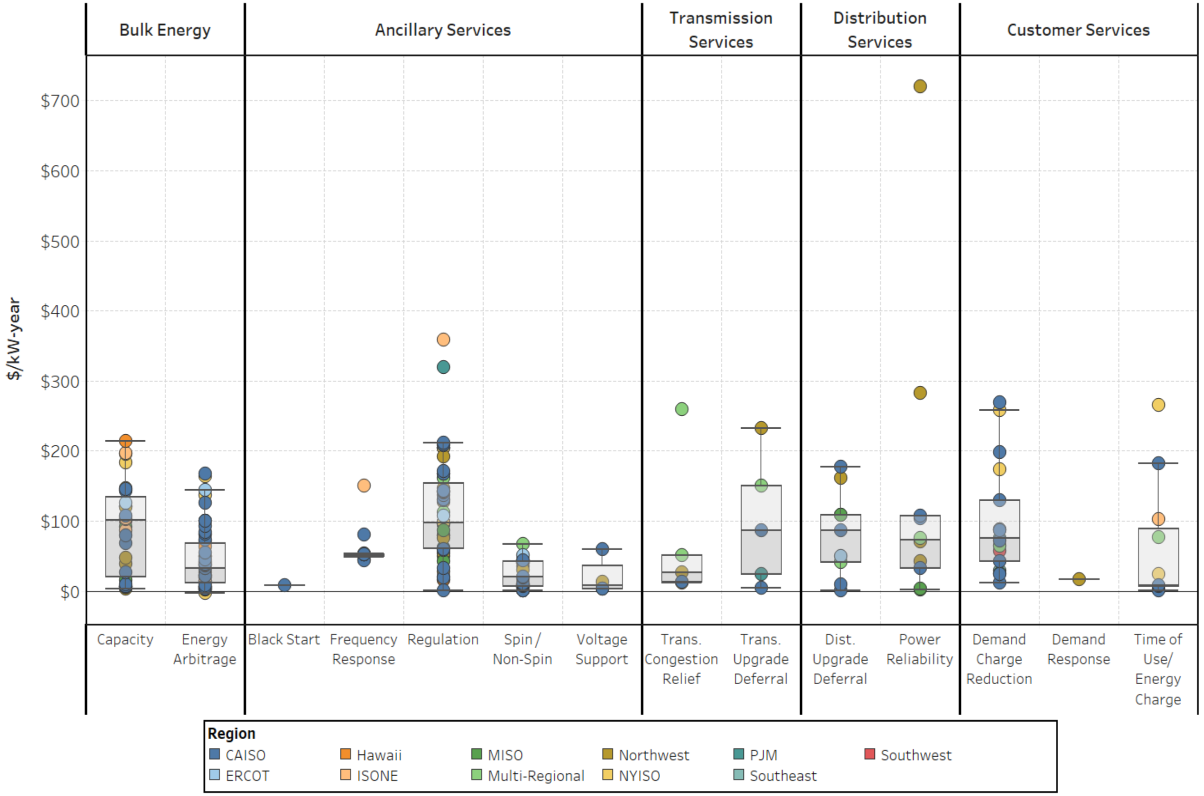
VALUATION TAXONOMY AND META-ANALYSIS RESULTS



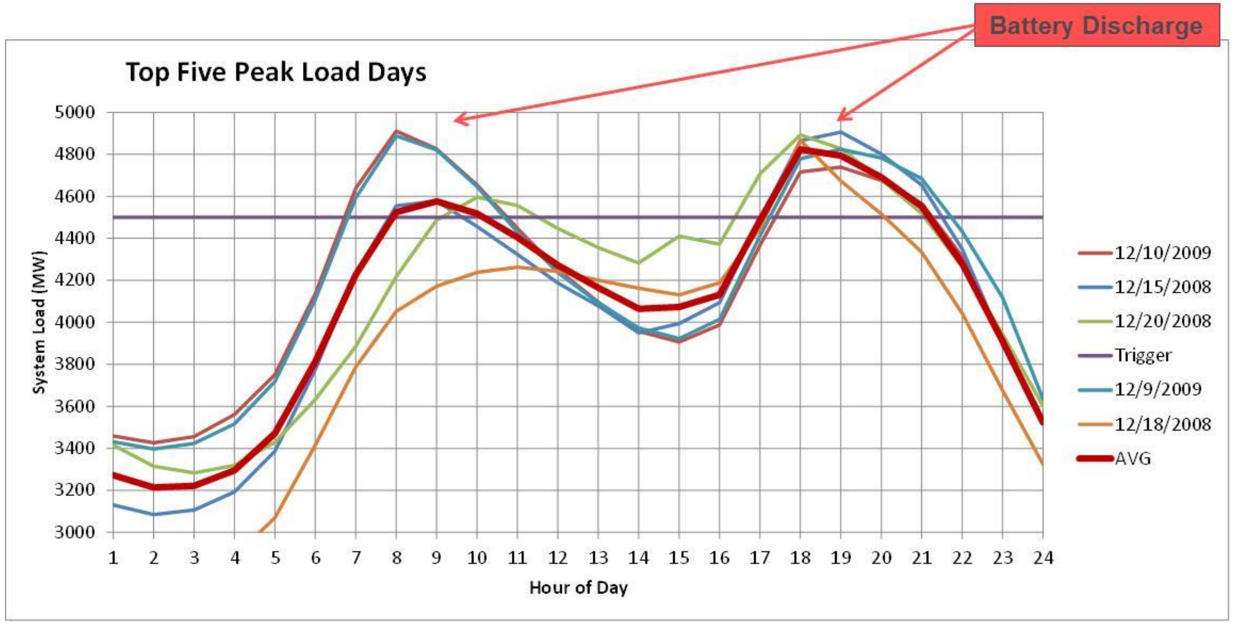
Category	Services
Bulk Energy Services	▫ Capacity or Resource Adequacy ▫ Energy Arbitrage
Ancillary Services	▫ Regulation ▫ Load Following ▫ Spin/Non-Spin Reserve ▫ Frequency Response ▫ Flexible Ramping ▫ Voltage Support ▫ Black Start Service
Transmission Services	▫ Transmission Upgrade Deferral ▫ Transmission Congestion Relief
Distribution Services	▫ Distribution Upgrade Deferral ▫ Volt-VAR Control ▫ Conservation Voltage Reduction
Customer Services	▫ Power Reliability ▫ Time of Use (TOU) Charge Reduction ▫ Demand Charge Reduction



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.

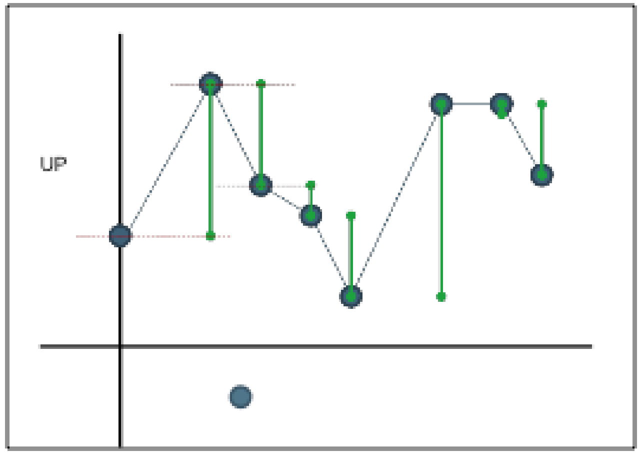
USE CASE EXAMPLE 1: CAPACITY / RESOURCE ADEQUACY

- 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, and
  - line losses.



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



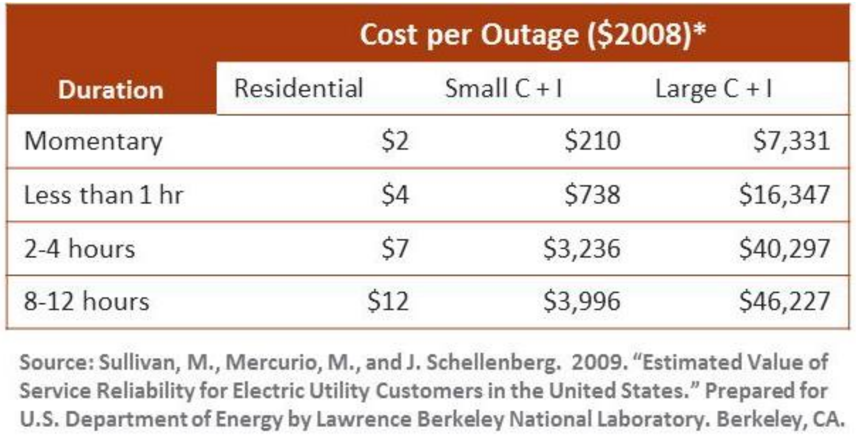
Mileage definition is the sum of all green bars in 15 min. intervals

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.

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



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.

USE CASE EXAMPLE 4: TRANSMISSION AND DISTRIBUTION DEFERRAL

- Energy storage used to defer investment; impact of deferment 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

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

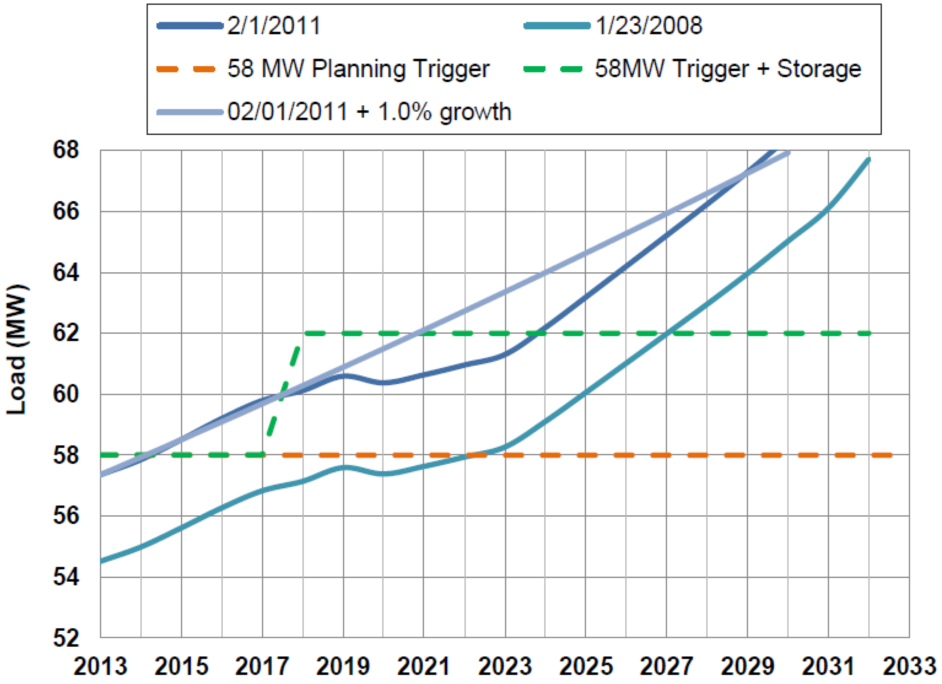
PV = Present value

FV = Future value

i = Cost of capital

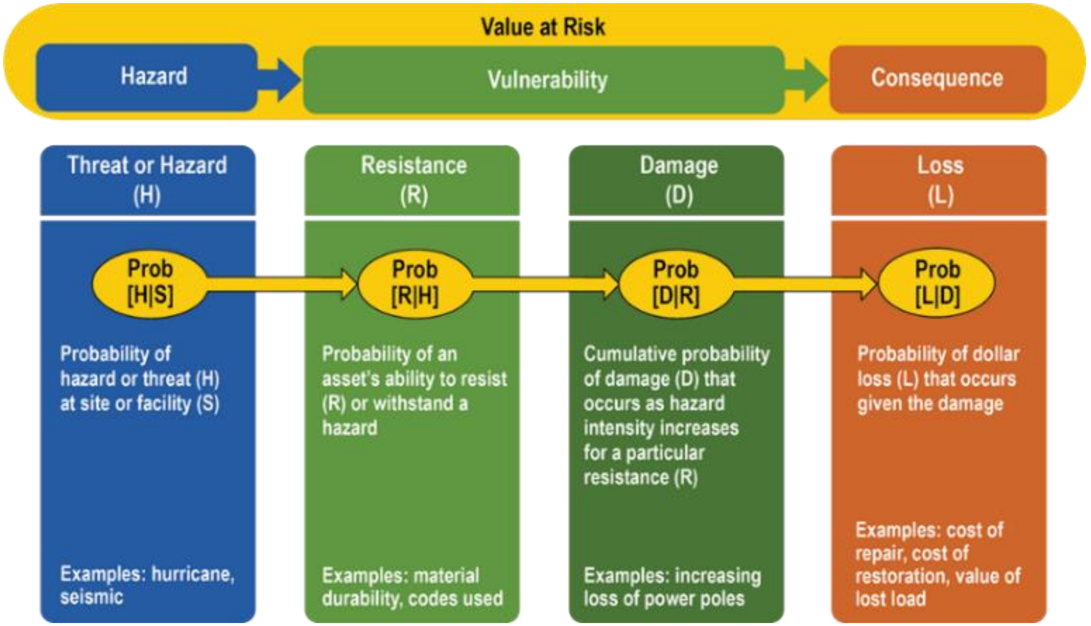
n = Number of years

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

- 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



Value at Risk

Hazard → Vulnerability → Consequence

Threat or Hazard (H)
Prob [H|S]
Probability of hazard or threat (H) at site or facility (S)
Examples: hurricane, seismic

Resistance (R)
Prob [R|H]
Probability of an asset's ability to resist (R) or withstand a hazard
Examples: material durability, codes used

Damage (D)
Prob [D|R]
Cumulative probability of damage (D) that occurs as hazard intensity increases for a particular resistance (R)
Examples: increasing loss of power poles

Loss (L)
Prob [L|D]
Probability of dollar loss (L) that occurs given the damage
Examples: cost of repair, cost of restoration, value of lost load

Pictorial Approach to Value Risk Assessment and Resilience Valuation

- 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

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

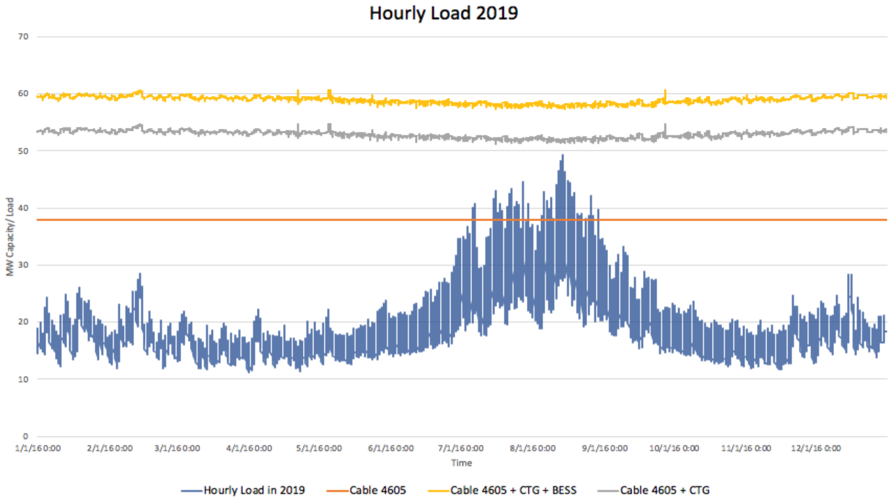
- Nantucket Island located off the coast of Massachusetts
  - Small resident population of 11,000; population swells to over 50,000 in summer
  - Nantucket's electricity supplied by two cables with a combined capacity of 71 MW and two small on-island combustion turbine generators (CTGs) with a combined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

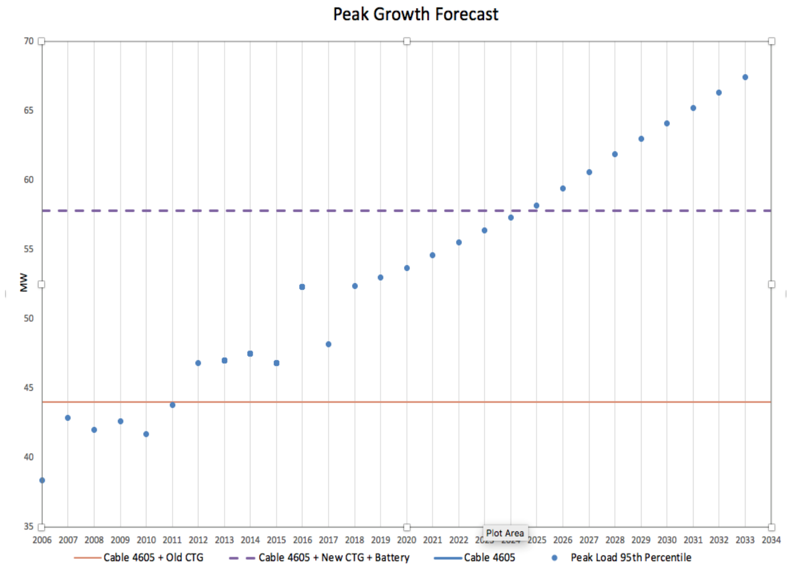
Nantucket Supply Cables

Source: Balducci, Patrick J., Alam, Md Jan E., McDermott, Thomas E., Fotedar, Vanshika, Ma, Xu, Wu, Di, Bhatti, Bilal Ahmad, Mongird, Kendall, Bhattarai, Bishnu P., Crawford, Aladsair J., and Ganguli, Sumitrra. Nantucket Island Energy Storage System Assessment. United States: N. p., 2019. Web. doi:10.2172/1564262.

BENEFITS OF LOCAL OPERATIONS

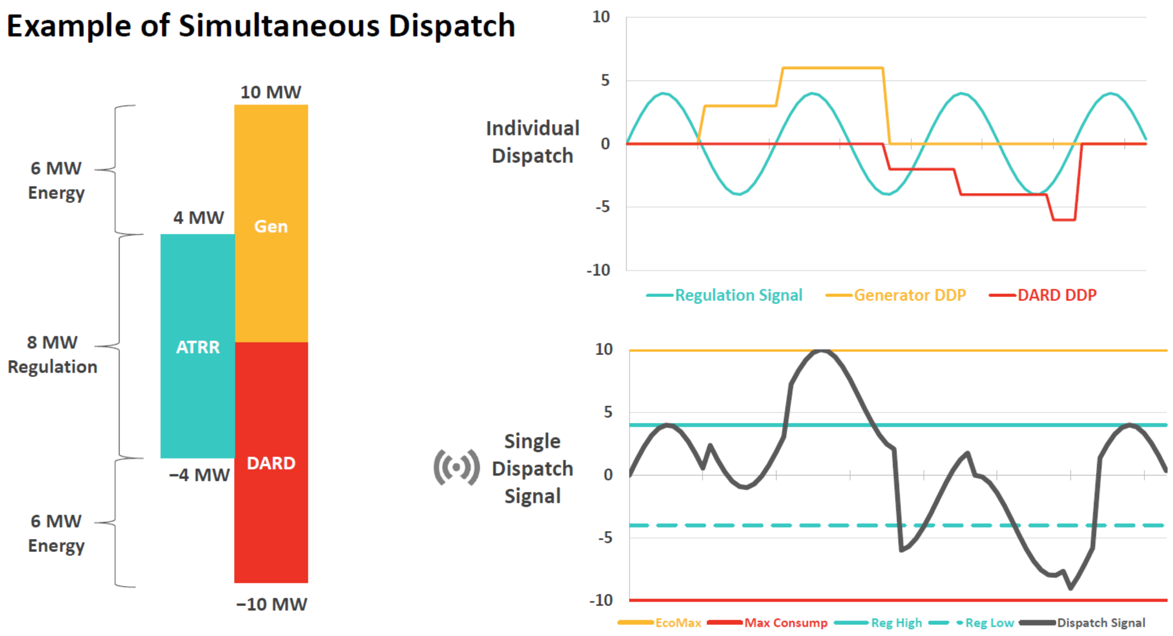
- The research team performed an extensive load analysis in order to define the n-1 contingency window and estimate the number of deferral years at 13
- Outage mitigation evaluated using historic outages and distribution system model
- Value of local operations ($122 million) exceeds the $93.3 million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





BENEFITS OF MARKET OPERATIONS

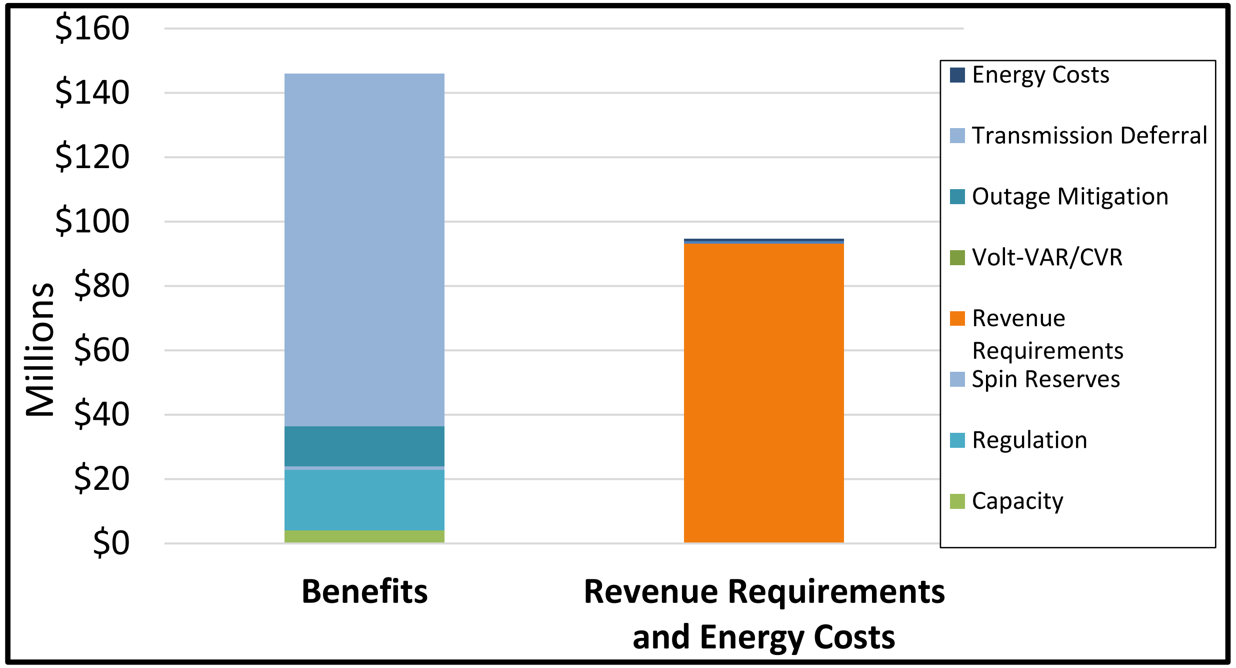
- Nantucket BESS modeled as a continuous storage facility
- BESS bid into markets using predicted prices – i.e., imperfect foresight
- Regulation follows energy neutral AGC signal with a performance score of 95%
- Market benefits estimated at $24.0 million over life of BESS
    - Regulation provides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



Simultaneous Dispatch of Continuous Storage Facility

NANTUCKET ISLAND CONCLUSIONS

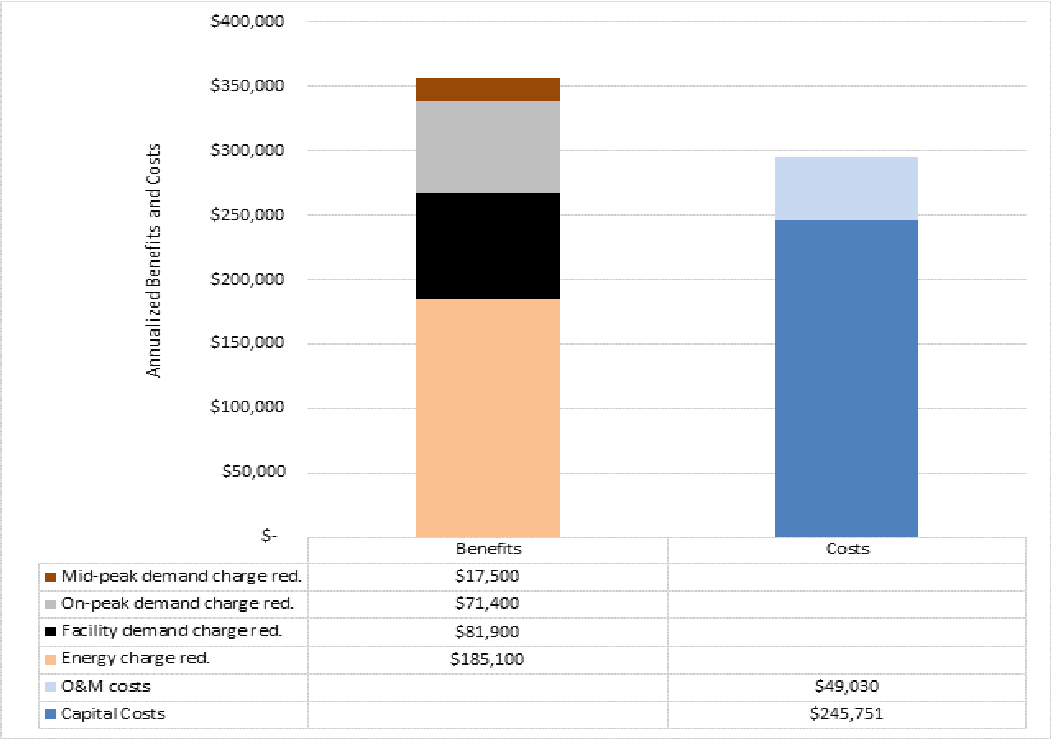
- Total 20-year pv benefits of BESS and CTG operations at $145.9 million exceed revenue requirements and energy costs at $93.9 million with an ROI ratio of 1.55
- Benefits largely driven by the transmission deferral use case, $109 million (75%) in PV terms
- Regulation services - $18.8 million, 13% of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



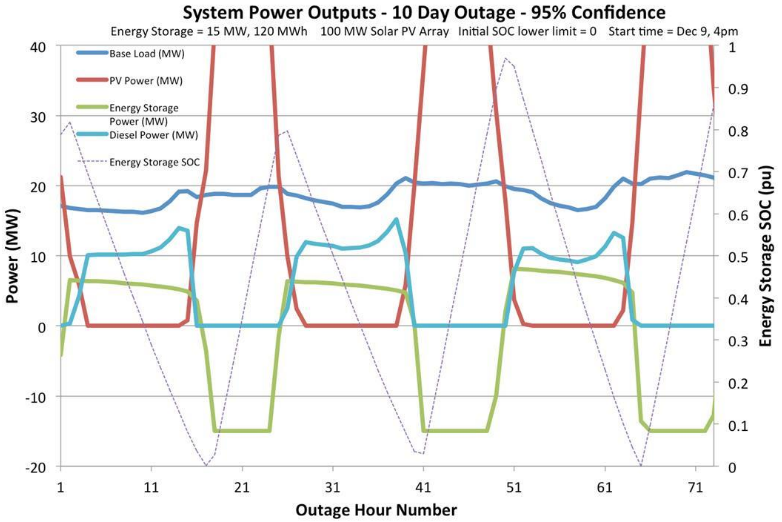
Benefits of Local and Market Operations (Base Case) vs. Revenue Requirements

JOINT FORCES TRAINING BASE LOS ALAMITOS

- JFTB Los Alamitos Microgrid Assessment
  - Resiliency goal – 90% survivability rate for a two-week outage
  - Energy assets – Photovoltaics, diesel gen sets, energy storage
  - Charge to analysts – Meet resiliency goal and maximize economic benefits given fixed budget

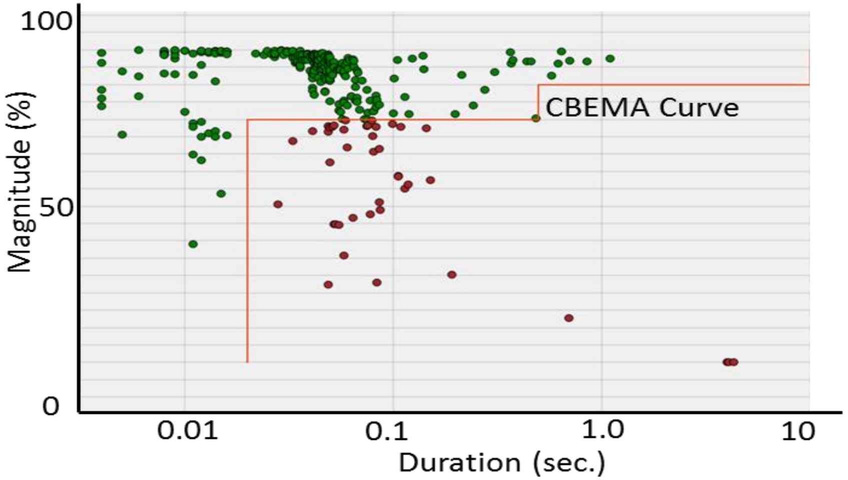


	Benefits	Costs
■ Mid-peak demand charge red.	$17,500	
■ On-peak demand charge red.	$71,400	
■ Facility demand charge red.	$81,900	
■ Energy charge red.	$185,100	
■ O&M costs		$49,030
■ Capital Costs		$245,751



Optimal Microgrid Scale Required to Achieve *Energy Security* and *Operational Goals:*
Gen Set – 1,150 kW
Photovoltaics – 1,224 kW
Energy storage – 408 kW / 510 kWh

TURNER ENERGY STORAGE PROJECT – VOLTAGE SAG COMPENSATION

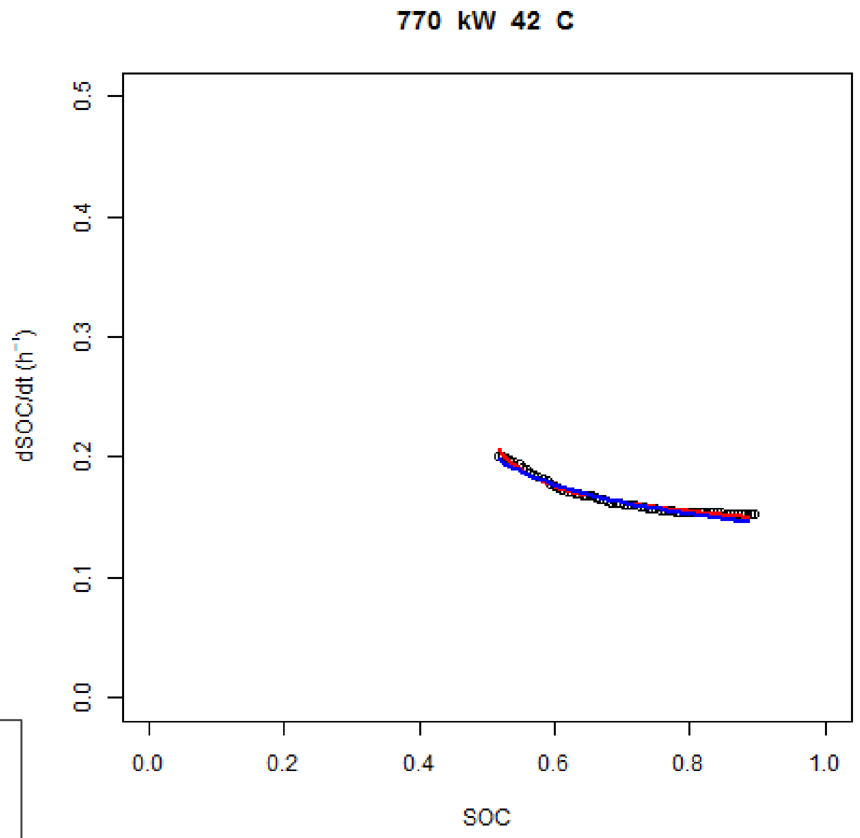


- Sustained voltage sags lead to production disruptions
- PNNL evaluated voltage data from 2014-2017 provided by Schweitzer Engineering Labs
- Applying the Computer Business Equipment Manufacturers (CBEMA) defined power quality curve, over 40 voltage sag events (<70% in magnitude, >20 milliseconds in duration) identified
- On average, two events per year identified as capable of causing disruptions
- In addition, outages of over 5 minutes were experienced three times between 2011 and 2016
- Each outage causes a minimum of three hours of downtime at a cost of $150,000 per hour

Source: Balducci, Patrick J., Mongird, Kendall, Alam, Jan E., Wu, Di, Fotedar, Vanshika, Viswanathan, Vilayanur V., Crawford, Aladsair J., Yuan, Yong, Labove, Garett, Richards, Shane, Shane, Xin, and Wallace, Kelly. Washington Clean Energy Fund Grid Modernization Projects: Economic Analysis (Final Report). United States: N. p., 2020. Web. doi:10.2172/1772558.

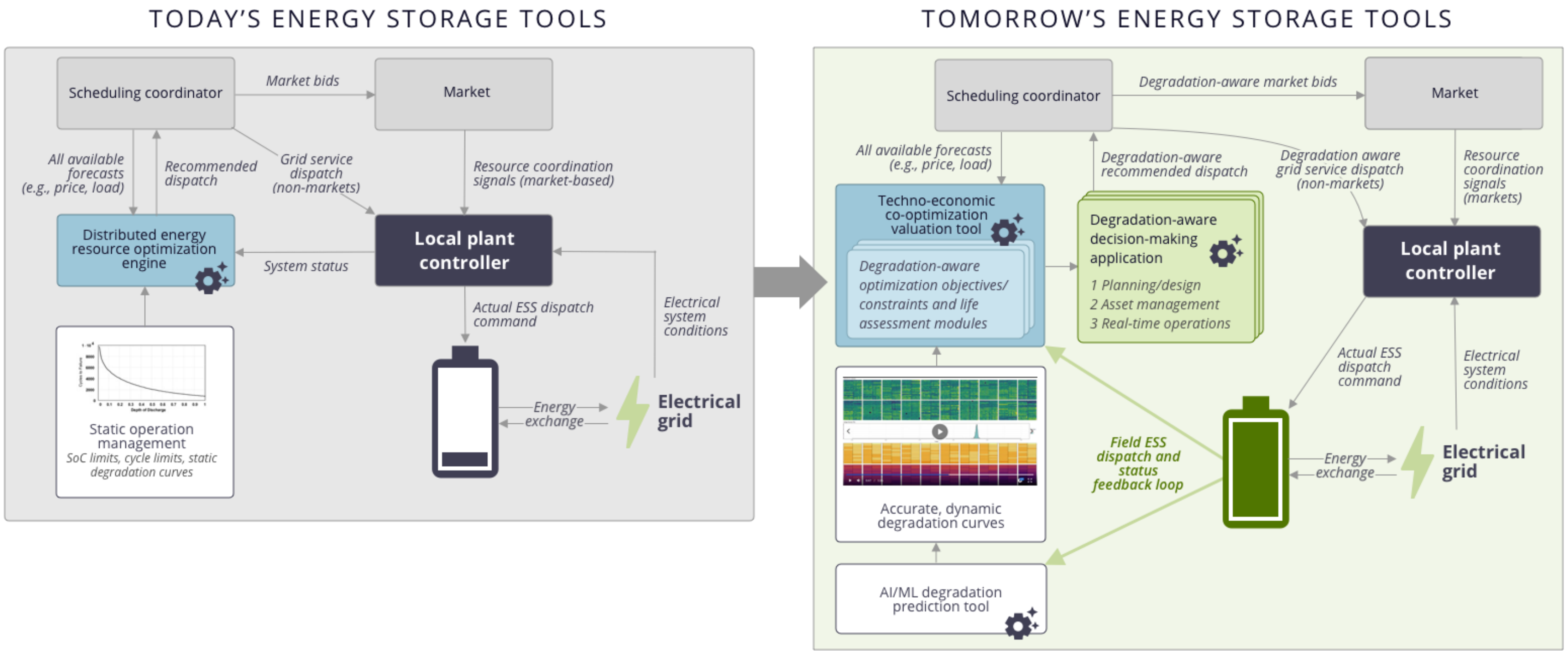
IMPORTANCE OF OPERATIONAL KNOWLEDGE IN CAPTURING ENERGY STORAGE VALUE

- 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"

CO-OPTIMIZING WITH PRECISE BATTERY DEGRADATION PREDICTIONS IS TRANSFORMATIONAL



TODAY'S ENERGY STORAGE TOOLS

Scheduling coordinator
Market bids
Market
All available forecasts (e.g., price, load)
Recommended dispatch
Grid service dispatch (non-markets)
Resource coordination signals (market-based)
Distributed energy resource optimization engine
System status
Local plant controller
Actual ESS dispatch command
Electrical system conditions
Static operation management
SoC limits, cycle limits, static degradation curves
Energy exchange
Electrical grid

TOMORROW'S ENERGY STORAGE TOOLS

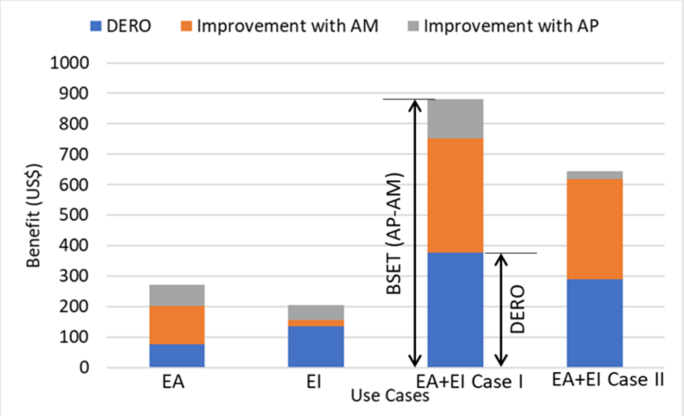
Scheduling coordinator
Degradation-aware market bids
Market
All available forecasts (e.g., price, load)
Degradation-aware recommended dispatch
Degradation aware grid service dispatch (non-markets)
Resource coordination signals (markets)
Techno-economic co-optimization valuation tool
Degradation-aware optimization objectives/ constraints and life assessment modules
Degradation-aware decision-making application
1 Planning/design
2 Asset management
3 Real-time operations
Local plant controller
Actual ESS dispatch command
Electrical system conditions
Field ESS dispatch and status feedback loop
Energy exchange
Electrical grid
Accurate, dynamic degradation curves
AI/ML degradation prediction tool

- 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.

DEVELOPMENT OF EFFECTIVE CONTROL SYSTEMS

- Field deployed commercially sourced optimizers – generally no dedicated process to keep track of the difference between ‘anticipated’ vs. ‘generated’ value – essentially an open loop process
- Reasons could be lack of adequate information/approach (logic, forecast error, lack of operational knowledge of energy storage system)
- Analytics to determine the reasons could close the loop and help improve the value generated

Illustrative results from a utility deployed ESS site

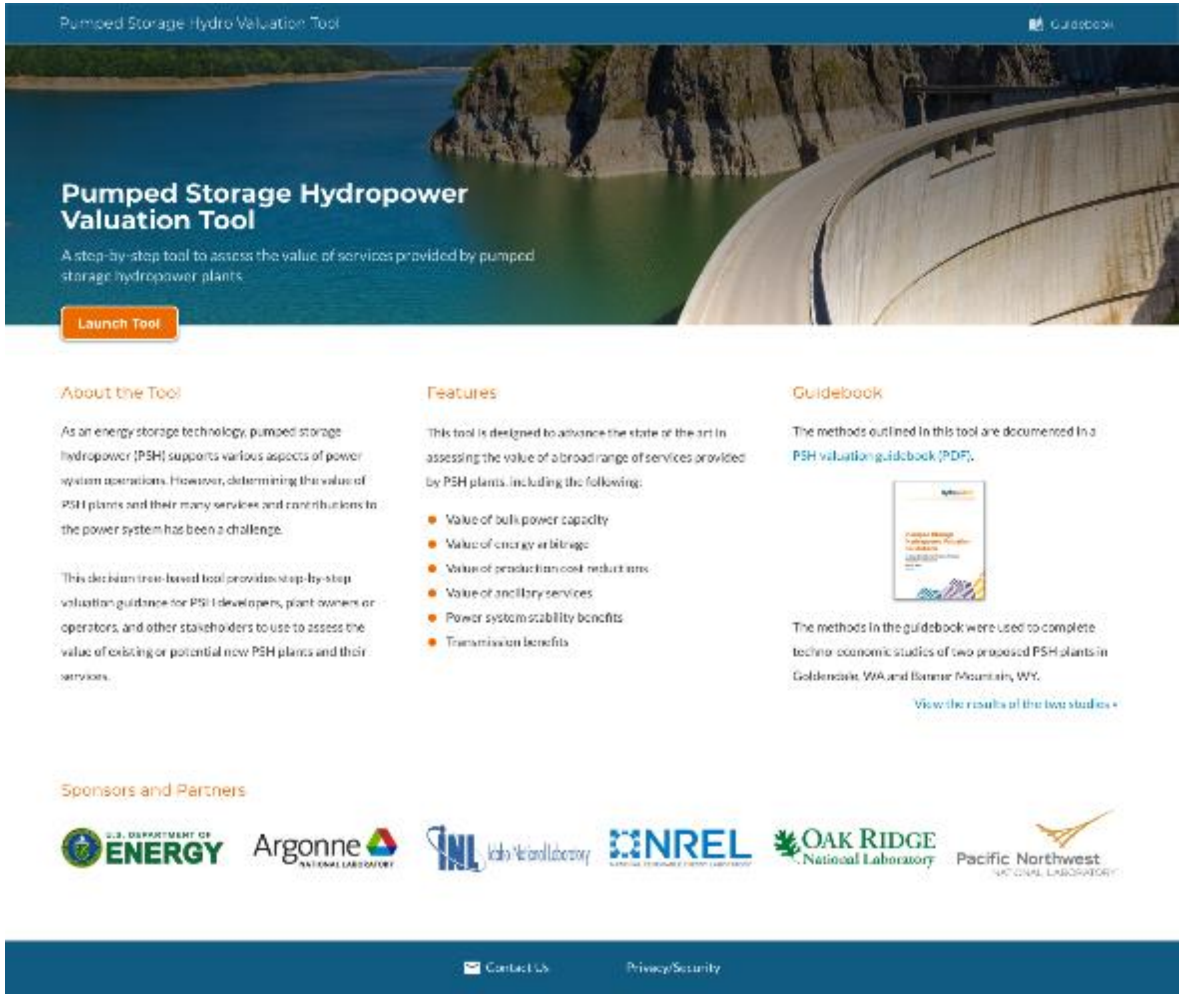


ESS Controller		**Use Case Benefits (US$)**			
		EA	**EI**	**EA+EI (Case I)**	**EA+EI (Case II)**
DERO	Without mathematical optimization considering financial information	75	134	377	290
BSET	Perfect ESS performance prediction	203	156	753	619
	Perfect price foresight and ESS performance prediction	272	204	881	643
Potential Improvement	With perfection in predicting ESS performance	128	22	376	329
	With perfection in forecasting price and predicting ESS performance	197	70	504	353

Potential Improvement

PUMPED STORAGE HYDRO (PSH) VALUATION TOOL LAUNCHED TODAY!

- PSH tool provides step-by-step valuation guidance for PSH developers, plant owners or operators, and other stakeholders
- PSH tool to advance state of the art in evaluating a broad set of use cases from three perspectives: owner/operator, system, and society
- PSH tool has a number of advanced features:
  - Embedded price-taker model
  - Multi-criteria decision analysis (MCDA) tool
  - Embedded financial worksheets and benefit-cost analysis (BCA) model
- Access tool at https://pshvt.egs.anl.gov/



Pumped Storage Hydropower Valuation Tool

A step-by-step tool to assess the value of services provided by pumped storage hydropower plants

About the Tool

As an energy storage technology, pumped storage hydropower (PSH) supports various aspects of power system operations. However, determining the value of PSH plants and their many services and contributions to the power system has been a challenge.

This decision tree-based tool provides step-by-step valuation guidance for PSH developers, plant owners or operators, and other stakeholders to use to assess the value of existing or potential new PSH plants and their services.

Features

This tool is designed to advance the state of the art in assessing the value of a broad range of services provided by PSH plants, including the following:

- Value of bulk power capacity
- Value of energy arbitrage
- Value of production cost reductions
- Value of ancillary services
- Power system stability benefits
- Transmission benefits

Guidebook

The methods outlined in this tool are documented in a PSH valuation guidebook (PDF).

The methods in the guidebook were used to complete techno-economic studies of two proposed PSH plants in Goldendale, WA and Banner Mountain, WY.

View the results of the two studies »

Sponsors and Partners

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

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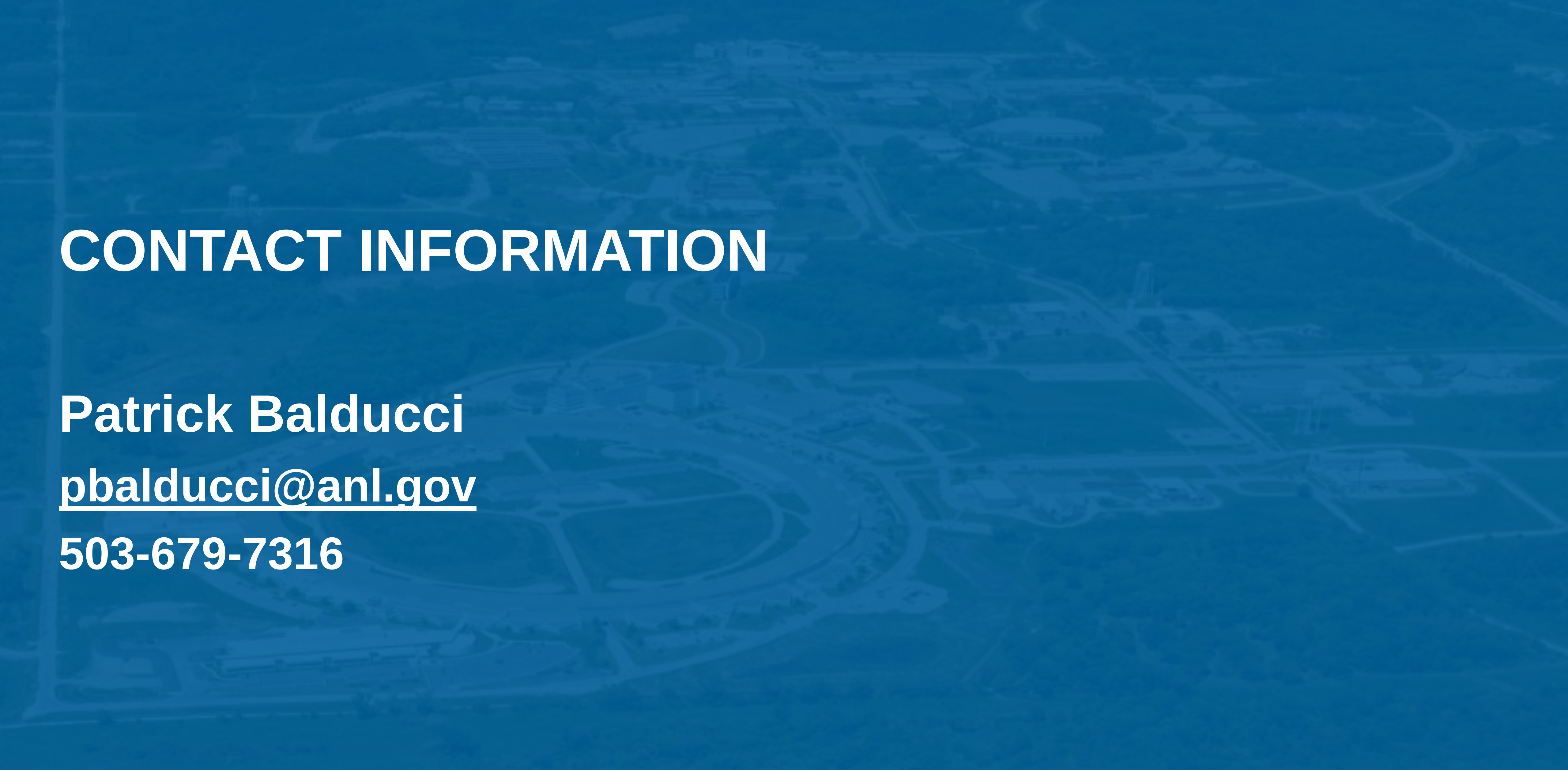
U.S. DEPARTMENT OF ENERGY

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



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