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INTRODUCTION TO ENERGY STORAGE ECONOMICS

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CALIFORNIA ENERGY COMMISSION LONG DURATION ENERGY STORAGE WEBINAR SERIES
SESSION 4: ECONOMICS AND FINANCING
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U.S. DEPARTMENT OF ENERGY

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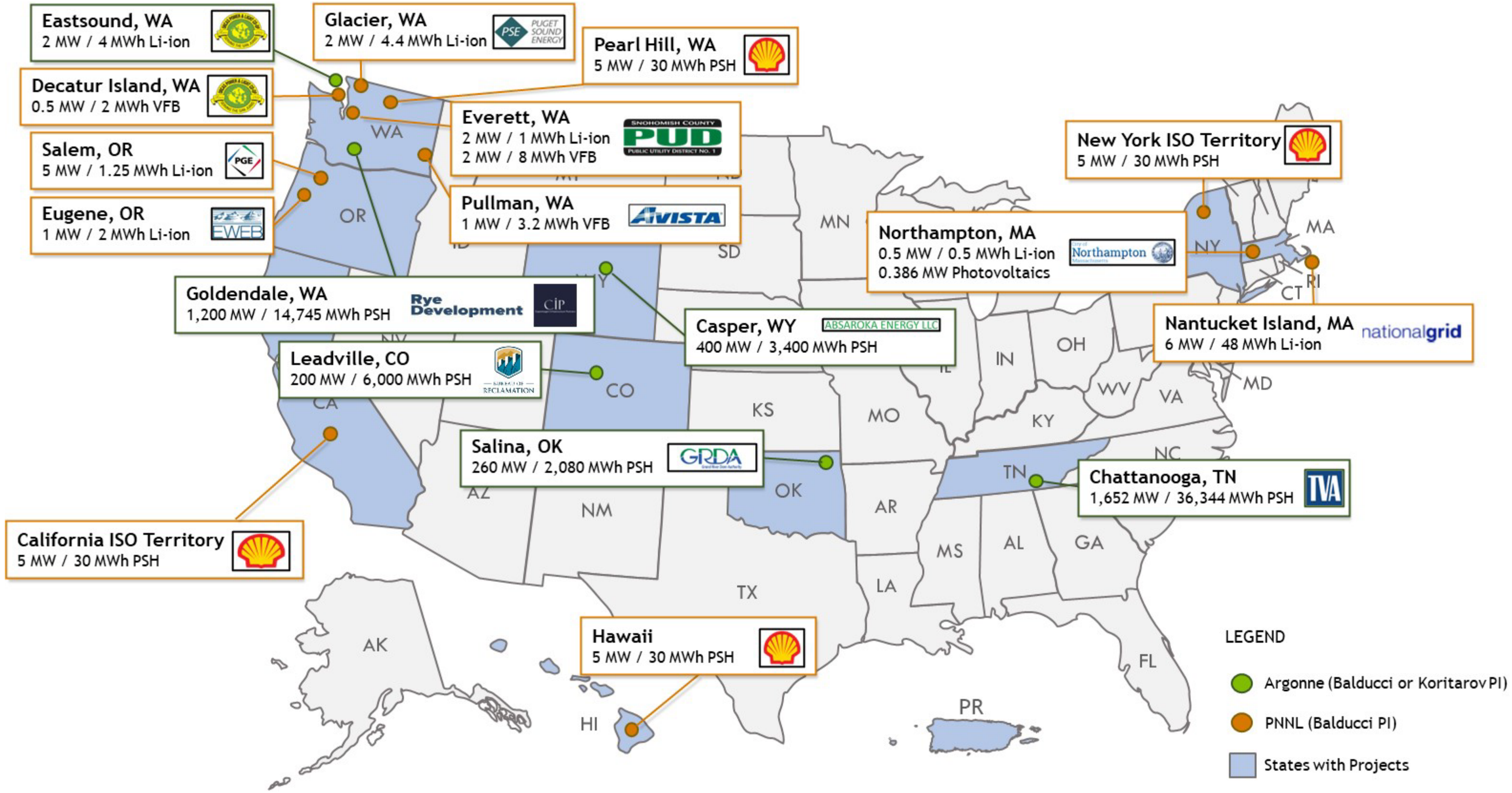
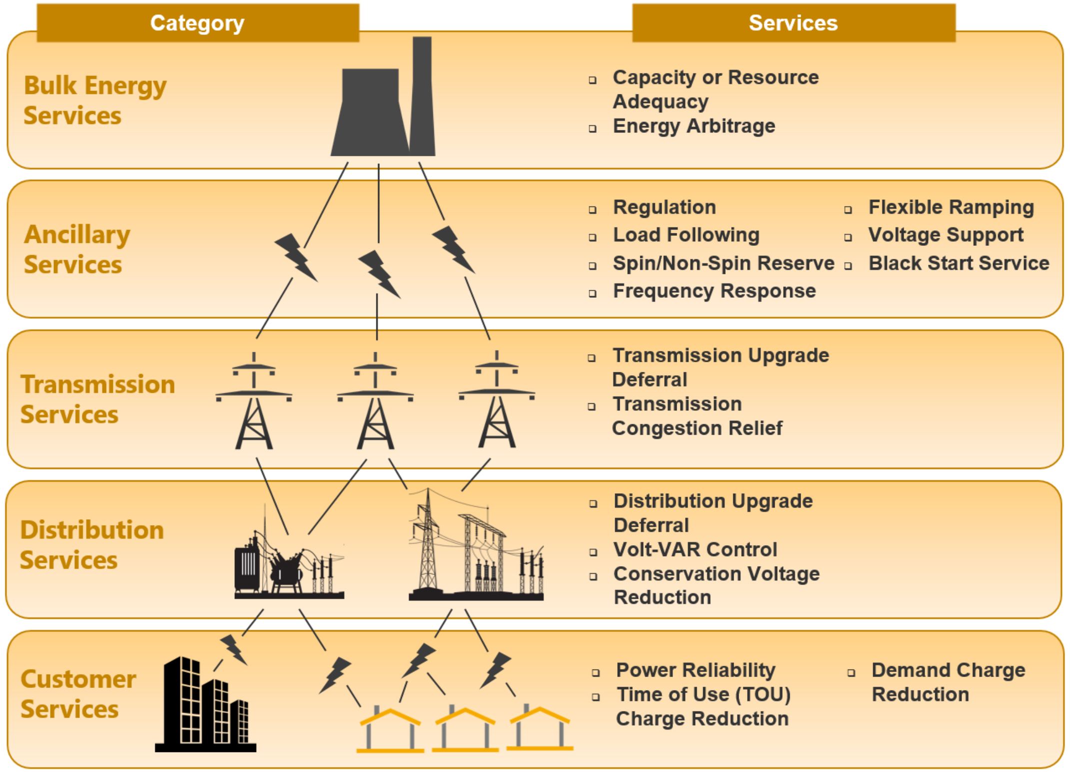
RECENT ENERGY STORAGE TECHNO-ECONOMIC ASSESSMENTS

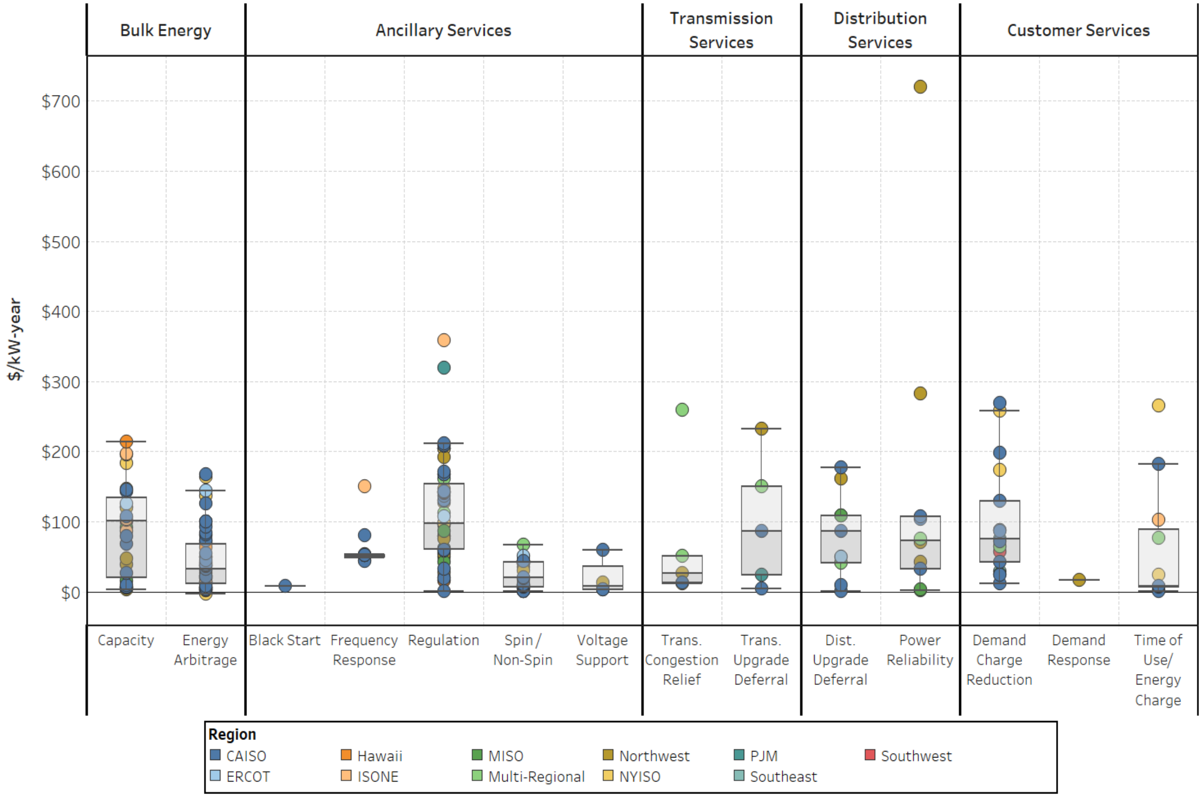


3,754	MW	62,763	MWh at	18	Sites

*Note that all projects highlighted in orange were led by Patrick Balducci during his tenure at Pacific Northwest National Laboratory.

VALUATION TAXONOMY AND META-ANALYSIS RESULTS

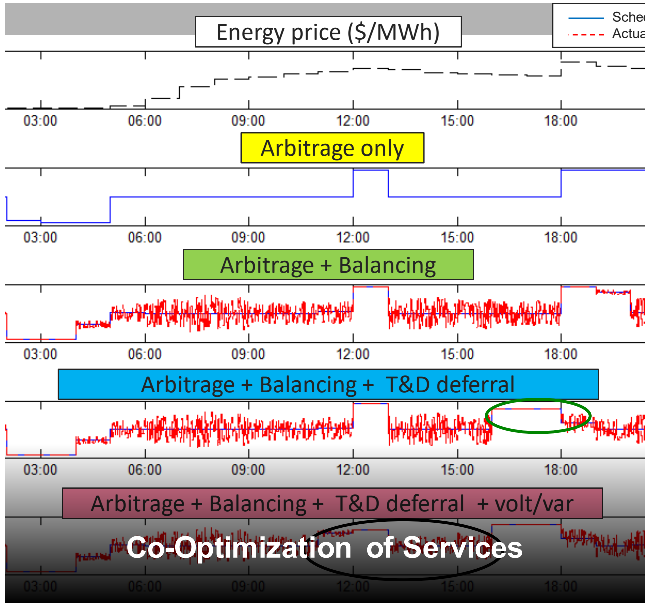




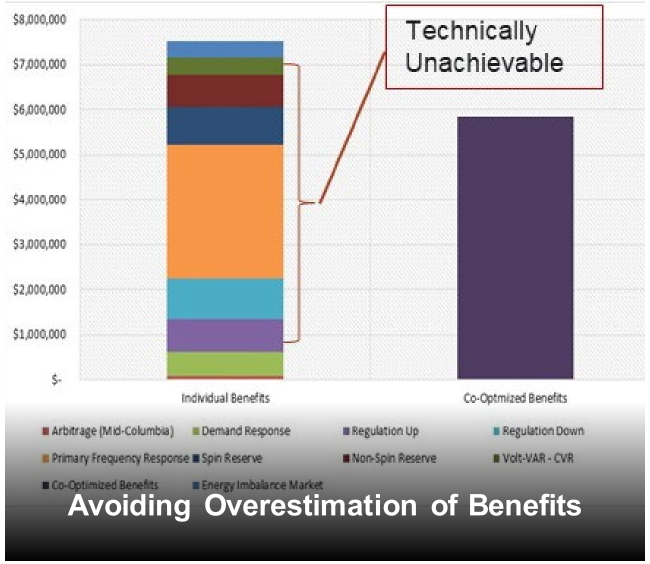
Source: Balducci, Patrick, Mongird, Kendall, and Weimar, Mark. Understanding the Value of Energy Storage for Power System Reliability and Resilience Applications. Germany: N. p., 2021. Web. https://doi.org/10.1007/s40518-021-00183-7.

CHALLENGES TO ACCURATELY ESTIMATING ECONOMIC BENEFITS

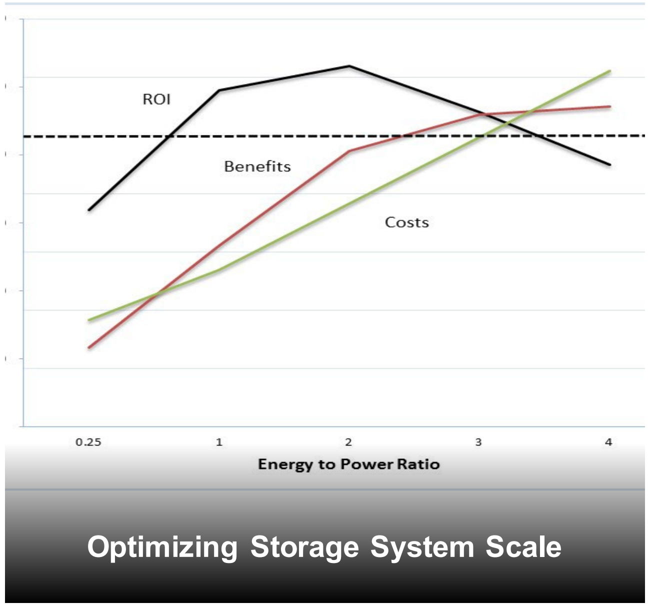
- Multidimensional competition for energy – not all services can be provided simultaneously and there exists intertemporal competition for energy
- Economic results are sensitive to sizing of energy storage system in terms of power and energy capacities
- Markets are complex and common practices of assuming 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
- Stochastic optimization



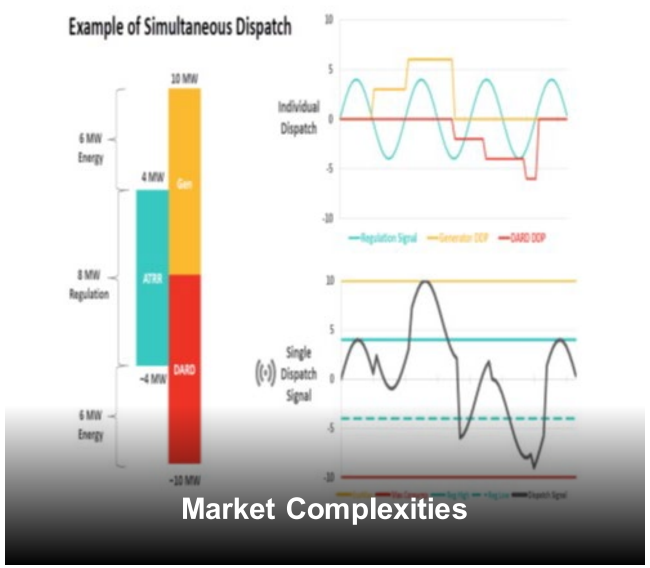
Co-Optimization of Services



Avoiding Overestimation of Benefits



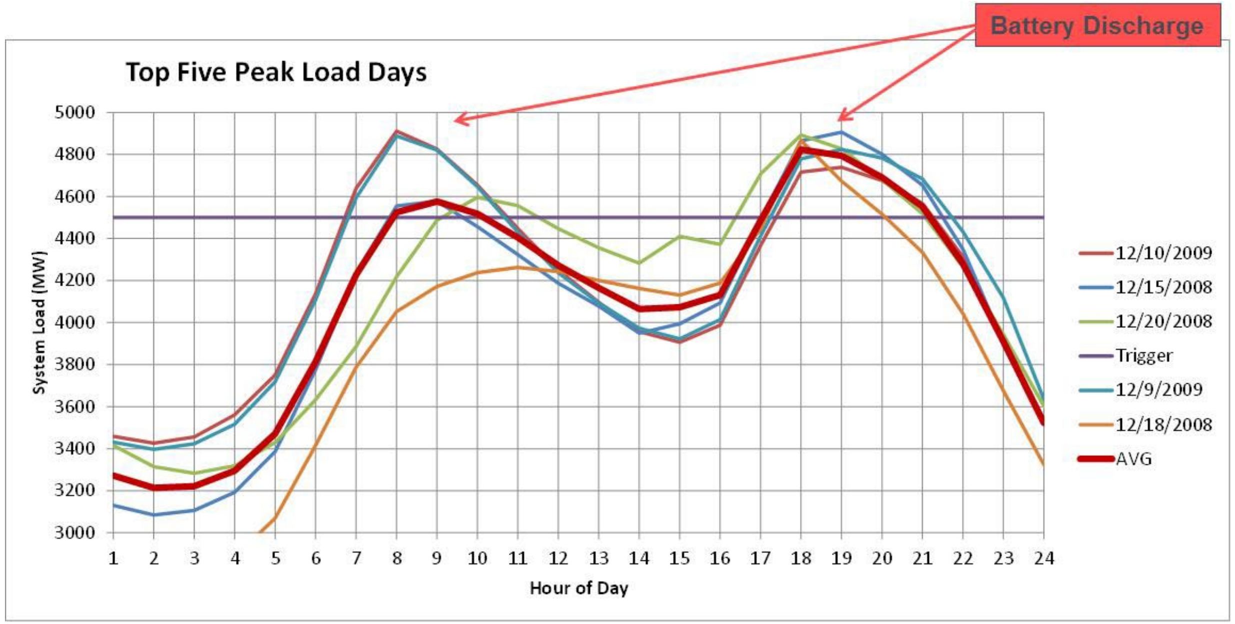
Optimizing Storage System Scale



Market Complexities

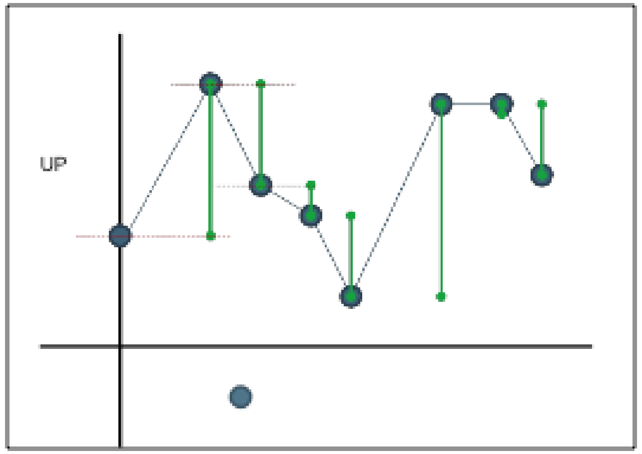
USE CASE EXAMPLE 1: CAPACITY / RESOURCE ADEQUACY

- 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



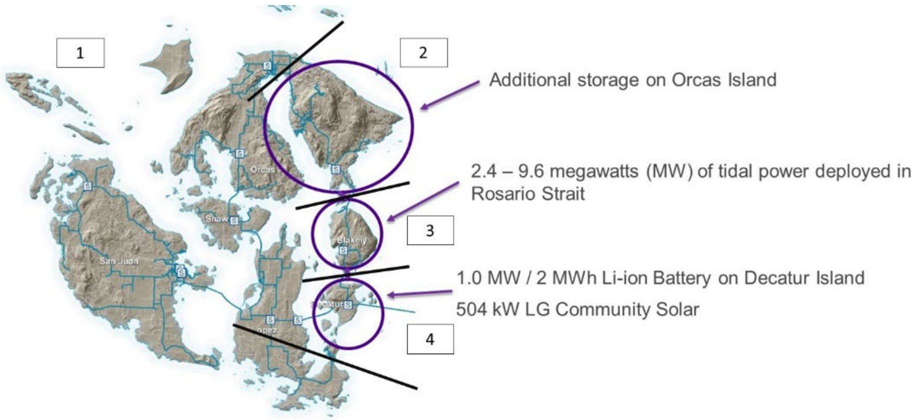
Mileage definition is the sum of all green bars in 15 min. intervals

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

	Cost per Outage ($2008)*		
Duration	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 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*

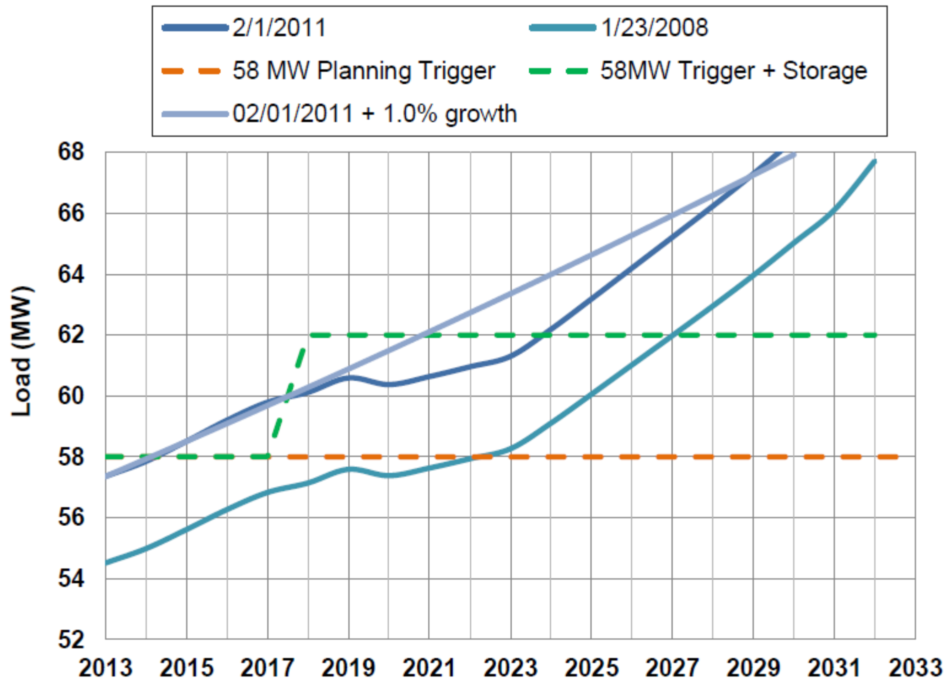
PV = Present value

FV = Future value

i = Cost of capital

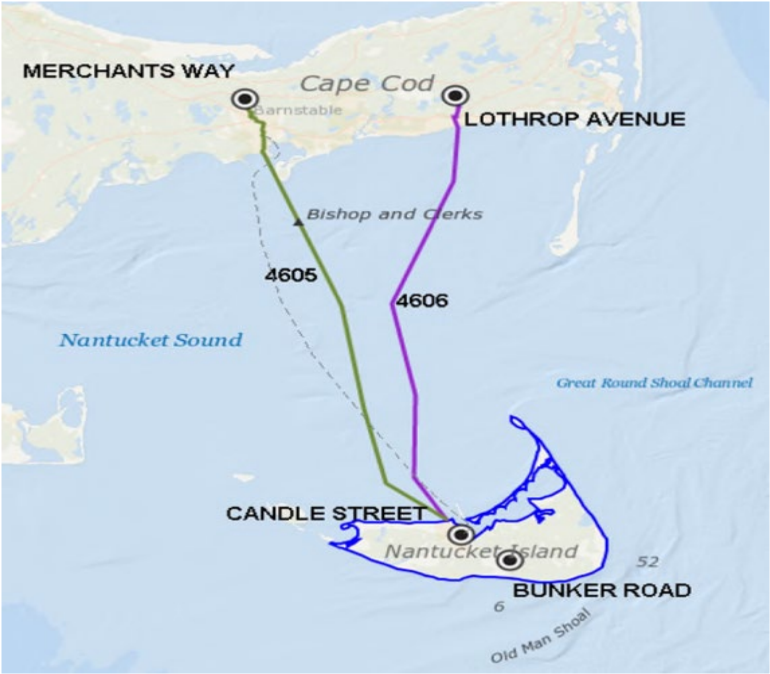
n = Number of years

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 million*1.03^6 / (1+.08)^6 = $7.5 million.*



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 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

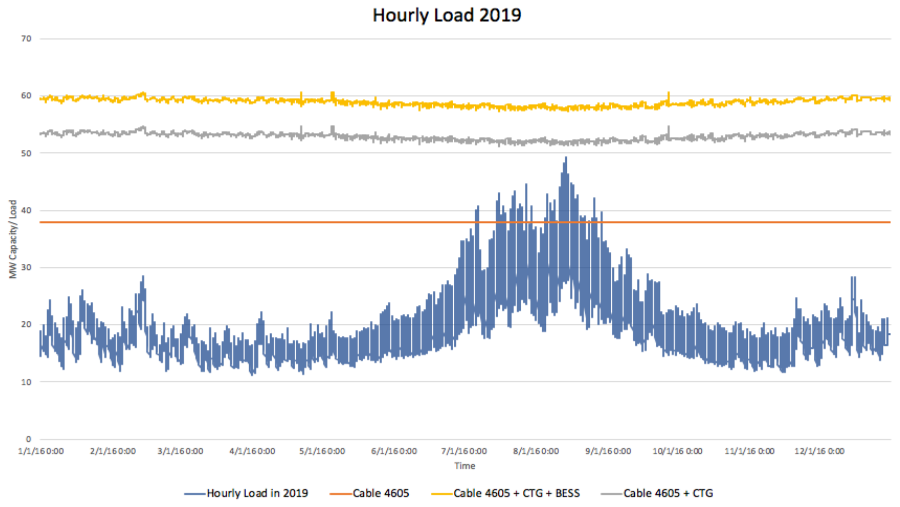


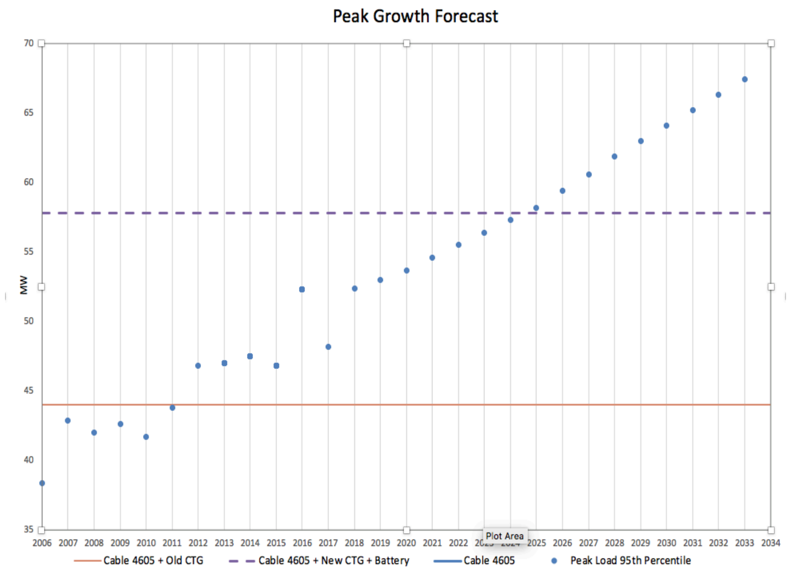
Nantucket Supply Cables

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

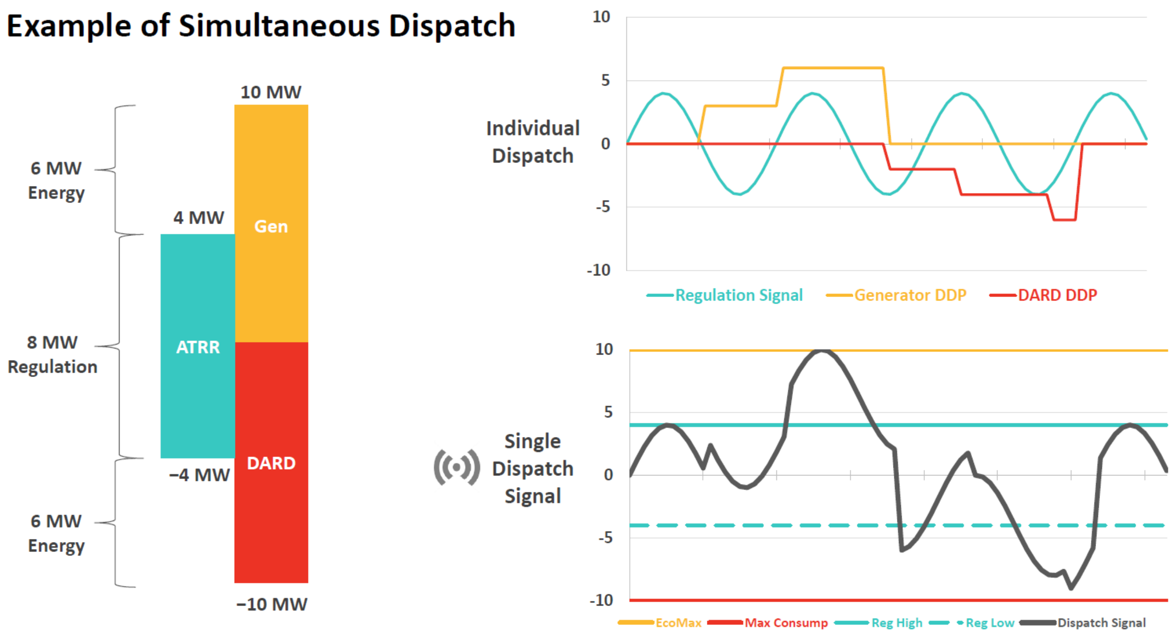
- The research team performed an extensive load analysis in order to define the n-1 contingency window and estimate the number of deferral years at 13
- Outage mitigation evaluated using historic outages and distribution system model
- Value of local operations ($122 million) exceeds the $93.3 million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





BENEFITS OF MARKET OPERATIONS

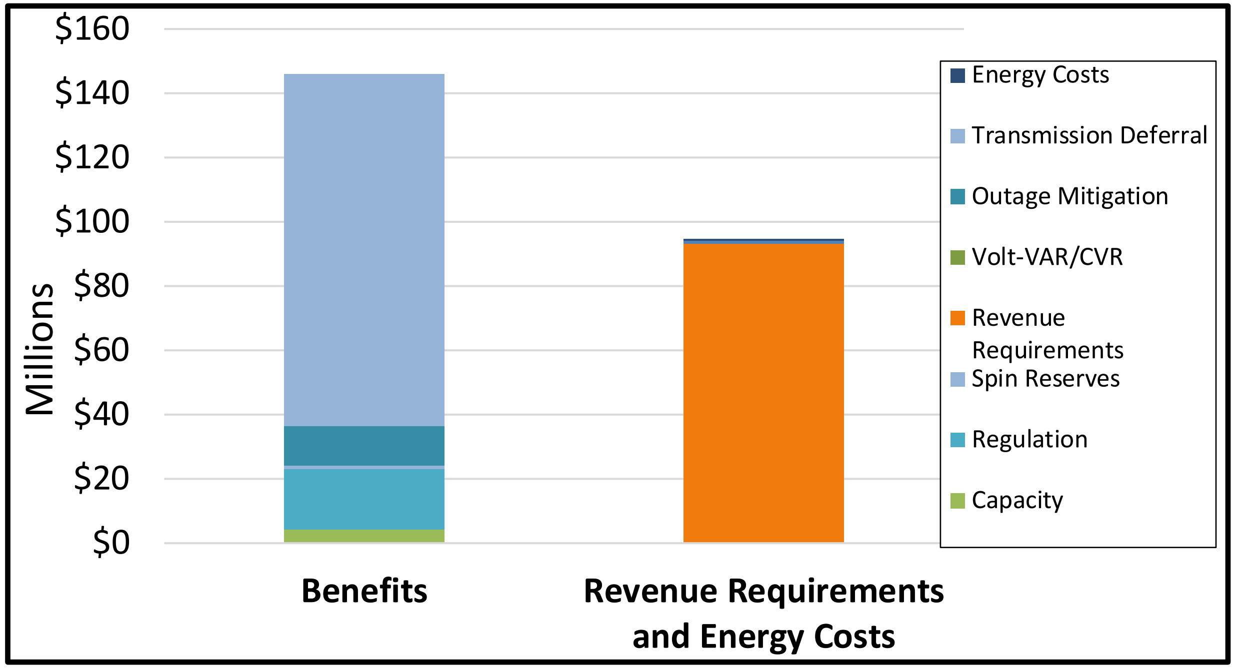
- Nantucket BESS modeled as a continuous storage facility
- BESS bid into markets using predicted prices – i.e., imperfect foresight
- Regulation follows energy neutral AGC signal with a performance score of 95%
- Market benefits estimated at $24.0 million over life of BESS
  - Regulation provides $18.8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

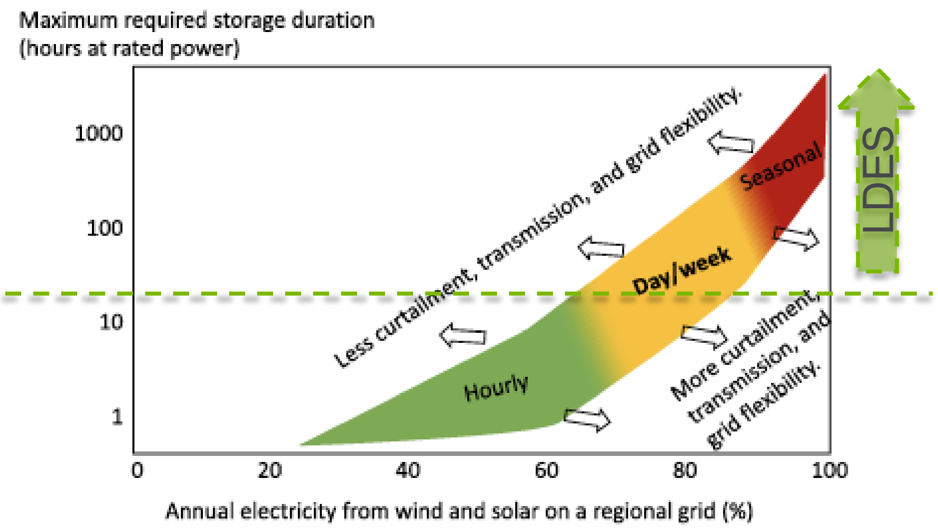
- Total 20-year pv benefits of BESS and CTG operations at $145.9 million exceed revenue requirements and energy costs at $93.9 million with an ROI ratio of 1.55
- Benefits largely driven by the transmission deferral use case, $109 million (75%) in PV terms
- Regulation services - $18.8 million, 13% of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



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

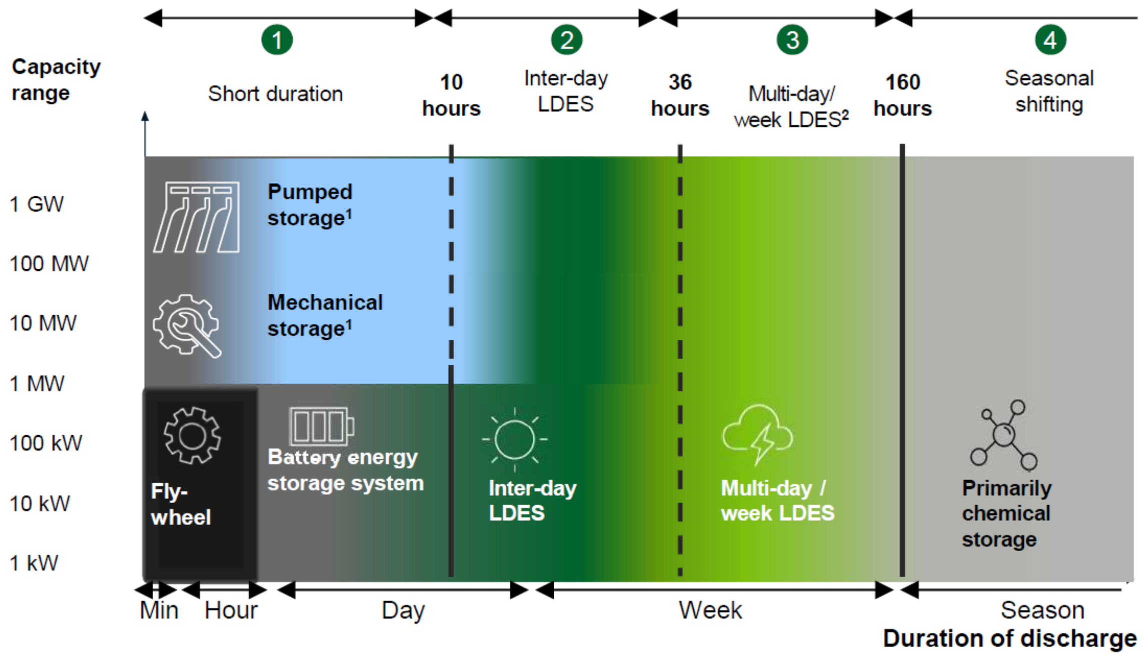
LONG DURATION ENERGY STORAGE (LDES) IS REQUIRED FOR DEEP DECARBONIZATION

Renewable Energy Penetration Necessitates LDES Investment



Source: Albertus et al. *Joule* (2020). Long-Duration Storage Applications, Economics, and Technologies.

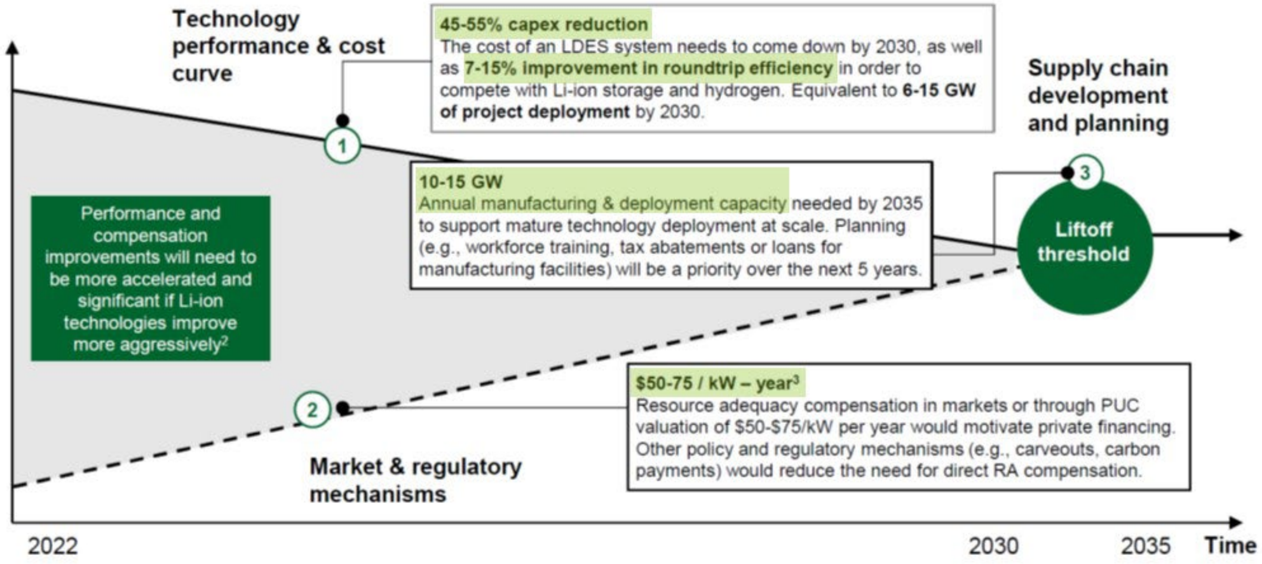
Renewable Energy Penetration Necessitates LDES Investment



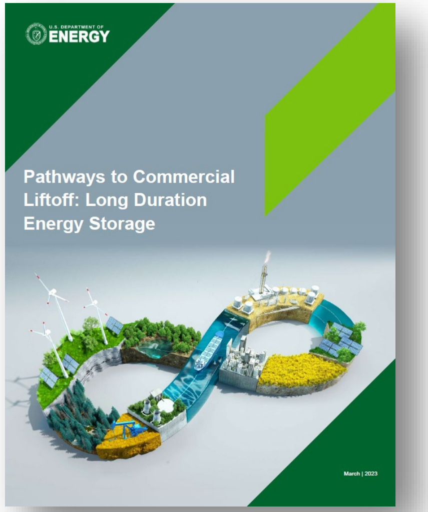
Source: U.S. Department of Energy. (2020). Pathways to Commercial Liftoff: Long Duration Energy Storage.

PATHWAYS TO COMMERCIAL LIFTOFF: LONG DURATION ENERGY STORAGE

- U.S. grid will need **225-460 GW of LDES** capacity by 2060, representing $330B in capital
- Net-zero pathways that deploy LDES result in **$10-20B in annualized savings** in operating costs and avoided capital expenditures (by 2050)



Improvements Needed in Technology, Cost, Regulation, and Supply Chain



LDES Pathways Report

USE CASE EXAMPLE 5: 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

Cost Element	Included in Outage Cost Studies	Included in Resilience Valuation
Value of lost load	☑	☑
Penalties to utilities		◌
Lost energy sales		◌
Surging LMPs	◌	◌
Fatalities, injuries, morbidity	◌	
Infrastructure and property damage	☑	
Business closures and relocations	◌	
Displacement costs	◌	
Direct, indirect, induced effects	☑	

☑ Often included.
◌ Sometimes included.
Rarely or never included left blank.

Treatment of Various Cost Elements Included in Outage Cost and Resilience Valuation Studies

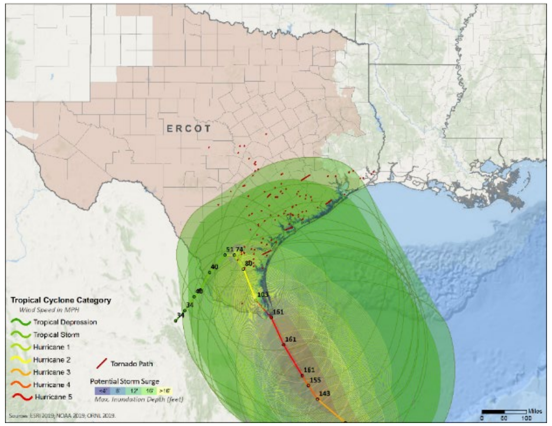
- Multi-hazard risk analysis that relies on expected value calculations based on probabilistic analysis, while addressing a broad range of hazards and values tied to lost economic productivity, infrastructure damage, and injuries/fatalities is required – annual risk premium
- More research is needed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

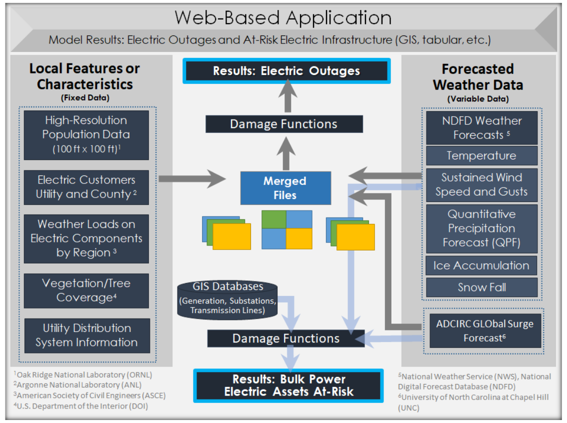
Source: Balducci, Patrick, Mongird, Kendall, and Weimar, Mark. Understanding the Value of Energy Storage for Power System Reliability and Resilience Applications. Germany: N. p., 2021. Web. https://doi.org/10.1007/s40518-021-00183-7.

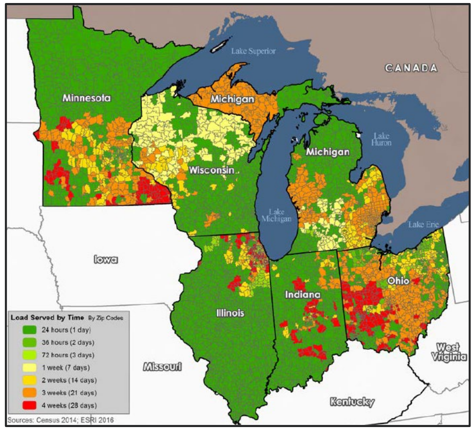
MULTI-HAZARD RISK ANALYSIS

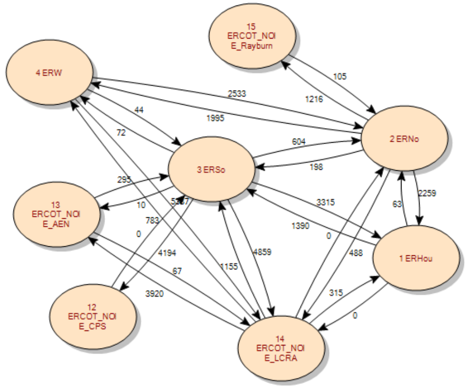
- LDES has demonstrated the capacity to enhance grid resilience, but resilience benefits are poorly defined and generally ignored in energy storage valuation studies and market structures.
- Reliability benefits are often evaluated using system models with inconsistent assumptions governing individual service values while resilience benefits are typically evaluated using customer damage functions and interruption cost studies, or sometimes evaluated using willingness to pay studies and input-output analysis.

- Multi-hazard risk analysis that relies on expected value calculations and an annual risk premium approach like the type used by insurers, while addressing a broad range of hazards and values tied to the value of lost load, surging locational marginal prices and potentially reduced economic productivity, would represent a significant advancement in the state of the art.
- Argonne has a suite of tools that can be used to evaluate the annualized risk premium associated with LDES' impact on resilience & reliability.









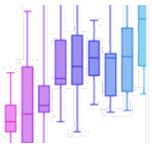
Threat Identification | Impact Assessment | Response & Recovery | Economic Valuation

FROM CLIMATE SCIENCE TO CAPACITY EXPANSION

Future Climate Scenarios

High-Frequency & High-Spatial Resolution Climate Model

Analyze and screen possible future weather patterns

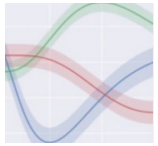


- Temperature
- Precipitation
- Wind/solar availability
- Extreme weather events

Climate to Grid Translation

Climate to Grid Translation Model

Generate probabilistic grid event scenarios

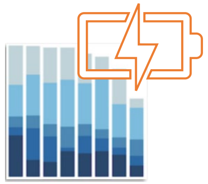


- Electricity demand
- Wind/solar profile
- Fuel supply constraints
- Grid asset de-rating
- Grid asset outage

Power System Planning with LDES

Argonne Low-carbon Electricity Analysis Framework (A-LEAF)

Power system capacity expansion planning and production cost simulations

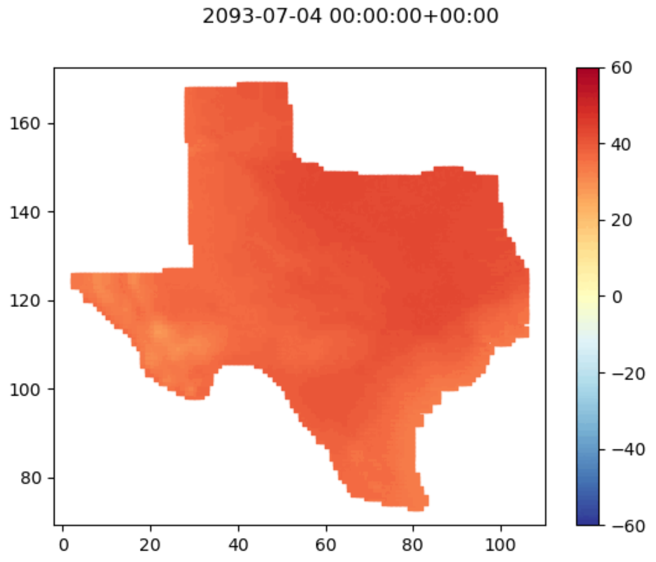


- Value of LDES
- Generation portfolio
- Generation scheduling
- Load curtailment
- Energy prices

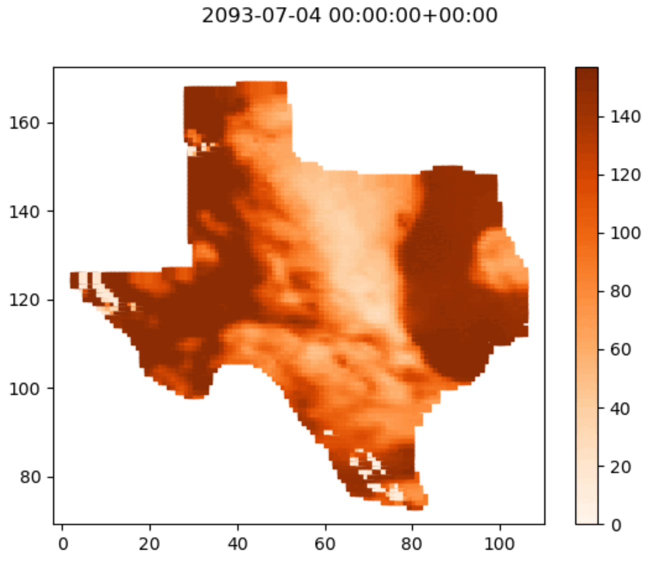
Argonne's Low-carbon Electricity Analysis Framework being Used to Evaluate the Role of LDES under Future Climate Scenarios and Extreme Weather Events

IDENTIFIED MULTIPLE HEAT- AND COLD-DRIVEN EVENTS

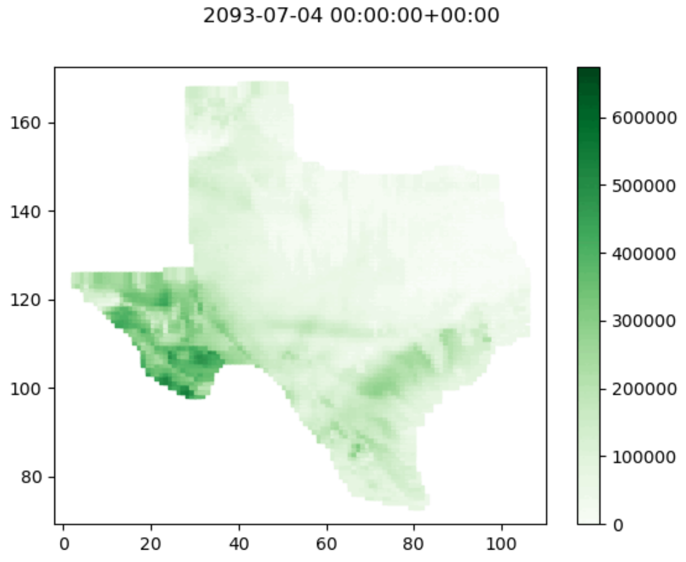
Hot: 2093 GFDL RCP8.5



Air Temperature [°C]



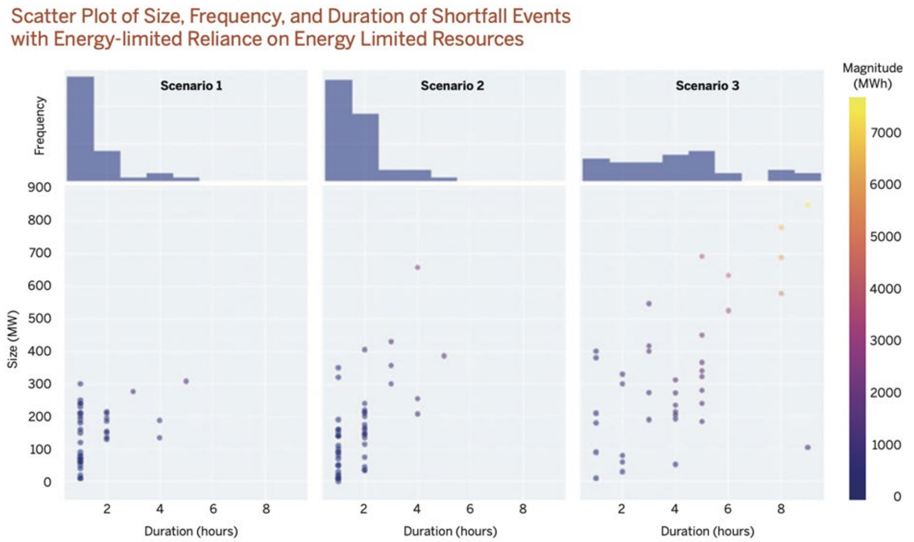
PV Output [MW]



Wind Output [kW]

NEW RESOURCE ADEQUACY METRICS WOULD MORE CLOSELY CAPTURE ROLE LDES CAN PLAY IN SUPPORTING RELIABILITY

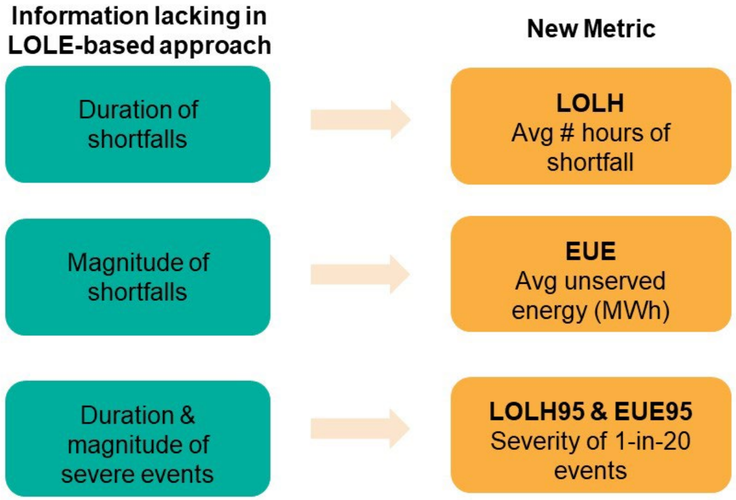
Three Scenarios with the Same LOLE but Varied Reliability Needs



Redefining Resource Adequacy for Modern Power Systems (ESIG, 2021)

Event Characteristic	Metric Affected	California Aug 2020	Texas Feb 2021	Difference
Number of Events	LOLEv	2 events	1 event	-50%
Number of Days	LOLE	2 days	3 days	+50%
Number of Hours	LOLH	6 hours	71 hours	+1,083%
Unserved Energy	EUE	2,700 MWh	990,000 MWh	+36,567%
Max Shortfall	-	1,072 MW	20,000+ MW	+1,766%

Beyond 1-day-in-10-years: : Measuring Resource Adequacy for a Grid in Transition. November 29, 2021 by Derek Stenclik - Telos Energy. https://www.esig.energy/beyond-1-day-in-10-years-measuring-resource-adequacy-for-a-grid-in-transition/



Balducci, P. and P. Levi (2024). *Improved Reliability and Resilience Valuation: Approaches and Metrics.* LDES National Consortium Annual Workshop. Commerce, CA.

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
Valuing Reliability and Resiliency	Nearly all storage benefits today are tied to energy and ancillary services; reliability and resilience service values are not adequately or consistently compensated
Regional Variation	Differentiate benefits by region and market structures/rules
Model Considerations	Models require greater granularity and fidelity in identifying days/hours when LDES will be required for grid and reliability services
Battery Characteristics	Accurate characterization of battery performance, including round trip efficiency rates across varying states of charge and battery degradation caused by cycling, is required

ACKNOWLEDGMENTS

Dr. Imre Gyuk, Caitlin Callaghan, and Mo Kamaludeen, DOE – Office of Electricity, Energy Storage Program

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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