Fundamentals of Energy Storage Valuation

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ENERGY STORAGE PROGRAM

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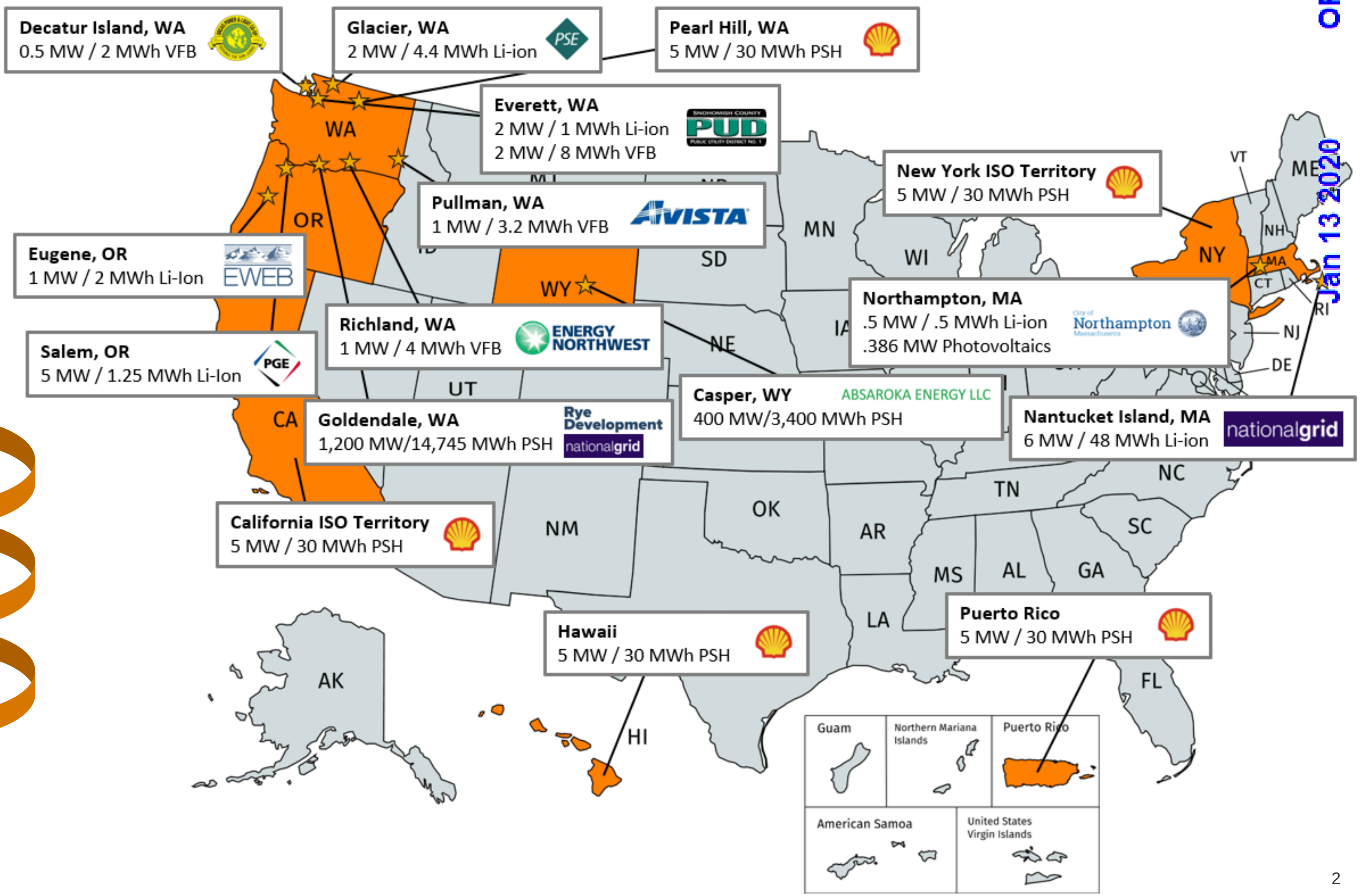
Energy Storage Techno-Economic Assessments at Pacific Northwest National Laboratory

PNNL Storage Analytics Program

1,626 MW 18,248 MWh at 16 Sites

PNNL Analytics Task-flow

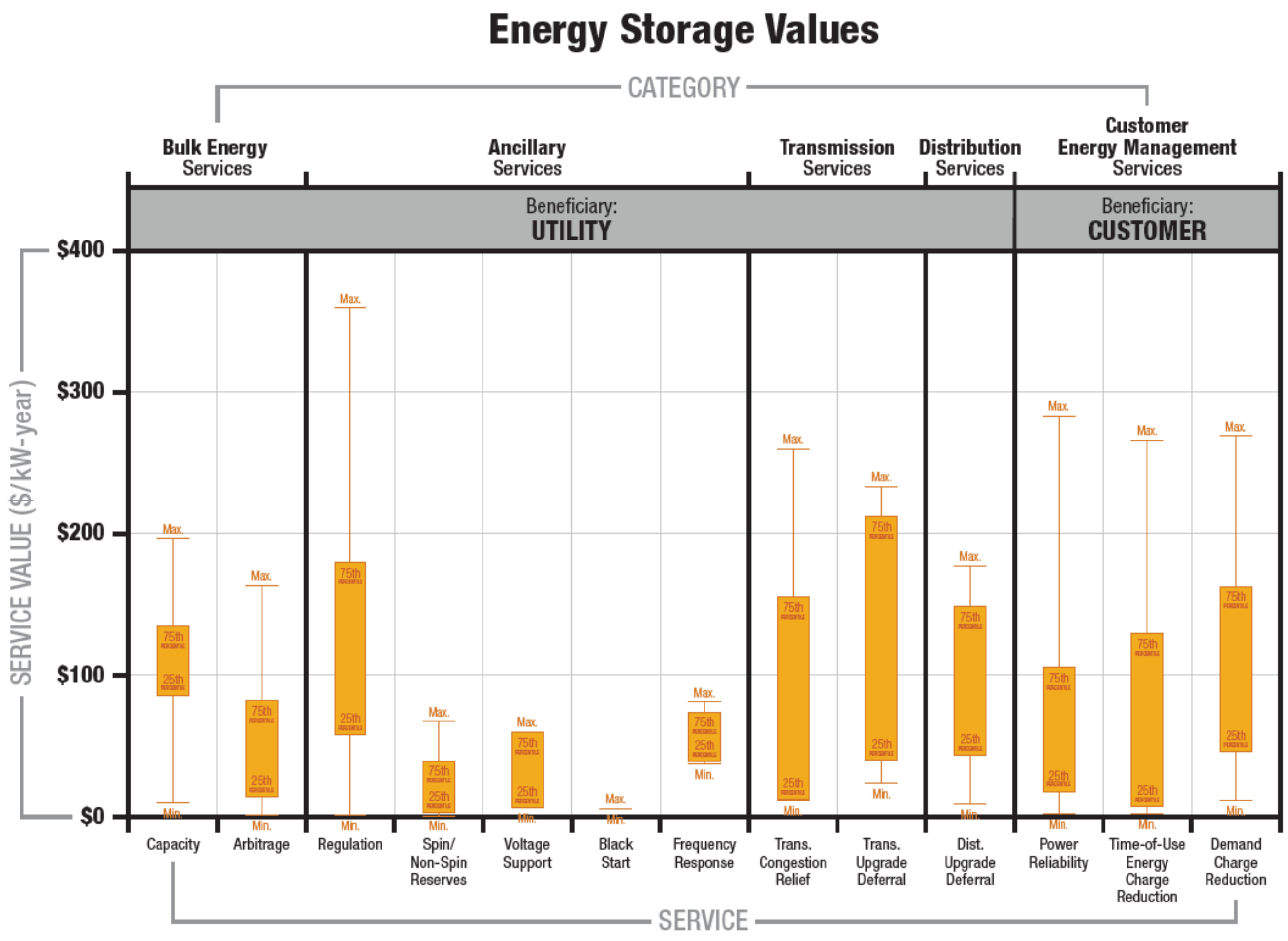
- Preliminary Economic Analysis and Identification of Use Cases
- Baseline Testing to Evaluate Ratings etc.
- Use Case Testing and Analysis
- Final Techno-Economic Analysis



Taxonomy of Energy Storage Services

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

Energy Storage Holds Tremendous Value



Key Lesson: The value of distributed energy resources accrues at multiple levels of the electric grid and there are no existing tools with all the required features to fully capture these values.

Source: Balducci, P., J. Alam, T. Hardy, and D. Wu. 2018. Assigning Value to Energy Storage Systems at Multiple Points in an Electrical Grid. Energy Environ. Sci., 2018, Advance Article. DOI: 10.1039/C8EE00569A. Available online at http://pubs.rsc.org/en/content/articlelanding/2018/ee/c8ee00569a#!divAbstract.

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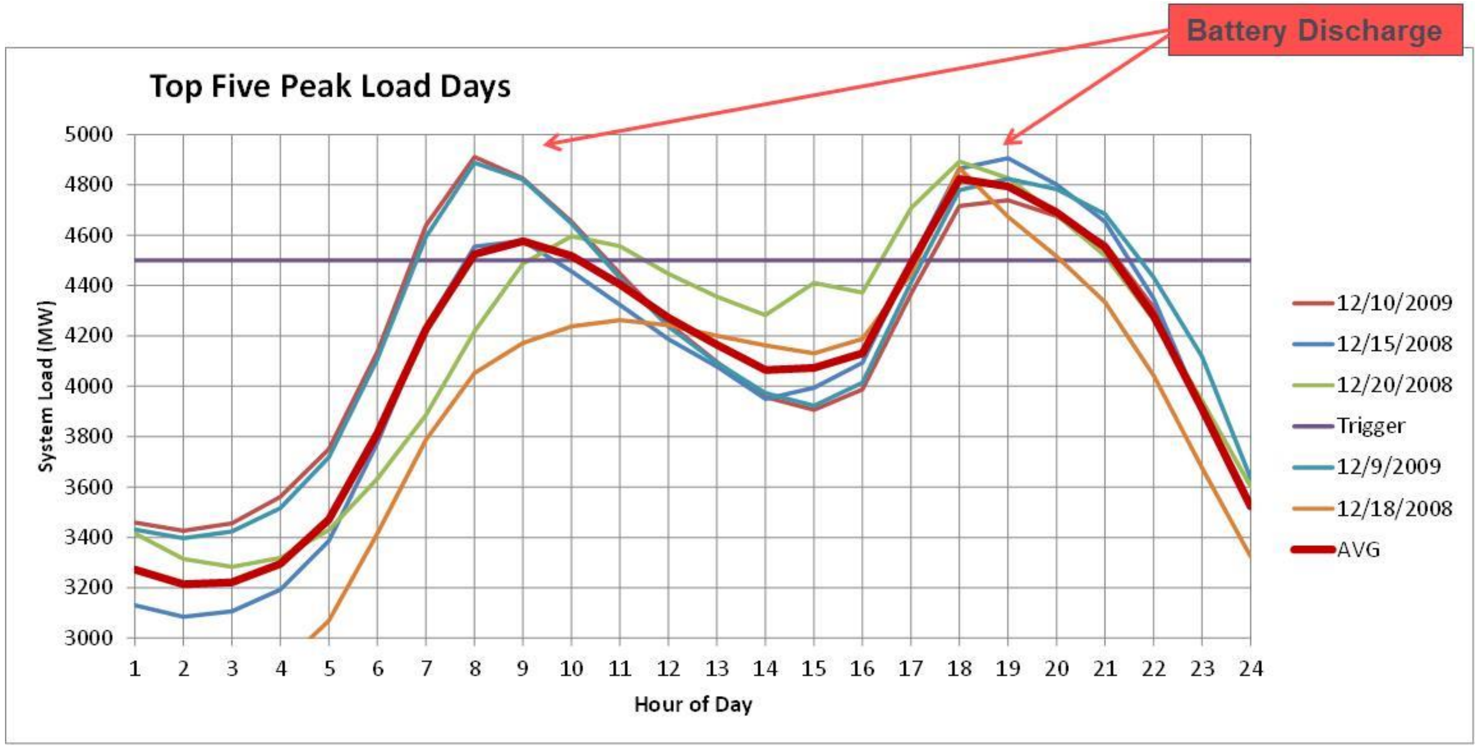
Capacity / Resource Adequacy

- 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
  - line losses.



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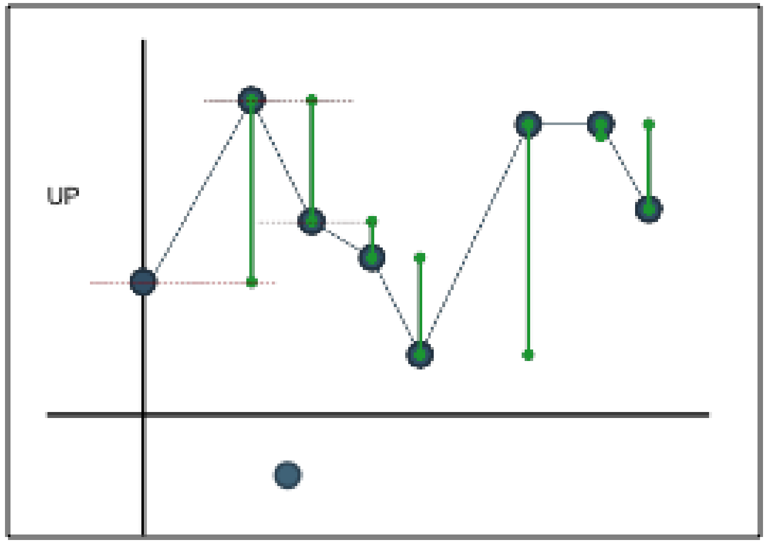
Frequency Regulation

- 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

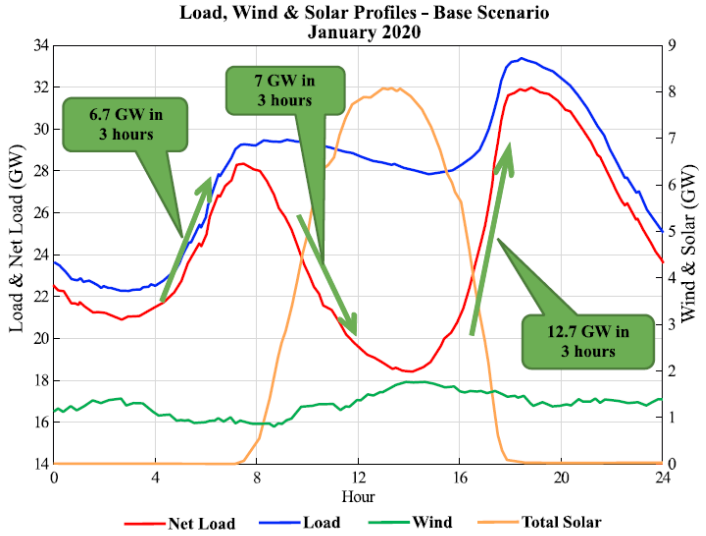
Capacity Payment = Regulation Capacity Clearing Price
Service Payment = Mileage or Service (AGC Signal Basis)
Performance = Regulation Service Performance Score

Key Lesson: Performance of battery storage in providing frequency regulation is exceptionally high. Batteries represent an efficient resource for providing frequency regulation; however, market prices can be driven downward as a result, undermining the profit potential to storage operators in the process.

Renewable Energy Time Shift and Capacity Firming

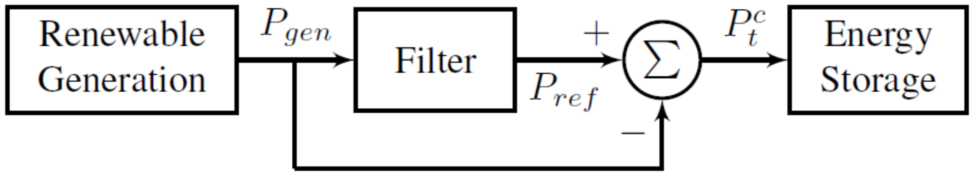
Renewable Energy Time Shift

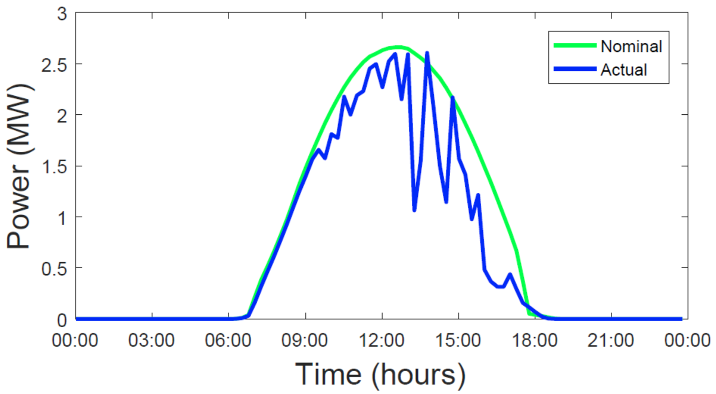
- Goal – shift renewable generation from off-peak to on-peak hours
- Example – CAISO "duck curve"
- CAISO has implemented a ramping product
- Other areas, arbitrage is your only option



Renewable Energy Capacity Firming

- Some areas are placing ramp rate limitations on renewable generation
  - Puerto Rico
  - Hawaii



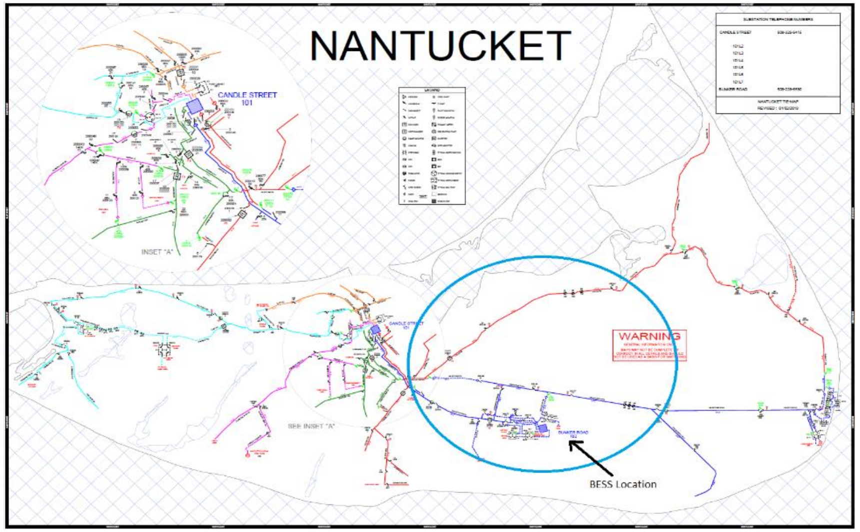


Outage Mitigation

- Outage data
  - Outage data obtained from utility for multiple years
  - Average annual number of outages determined; outages randomly selected and scaled to approximate average year
  - Outage start time and duration
- Customer and load information
  - Number of customers affected by each outage obtained from utility
  - Customer outages sorted into customer classes using utility data and assigned values
  - Load determined using 15-minute SCADA information

	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.



Modeled Outage on Nantucket Island

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

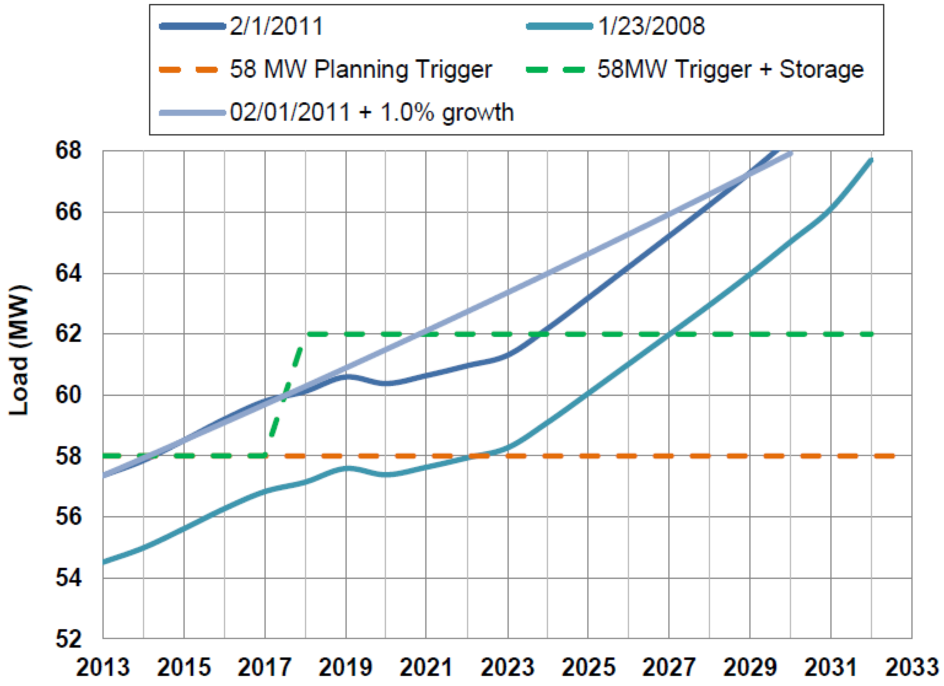
FV = Future value

i = Cost of capital

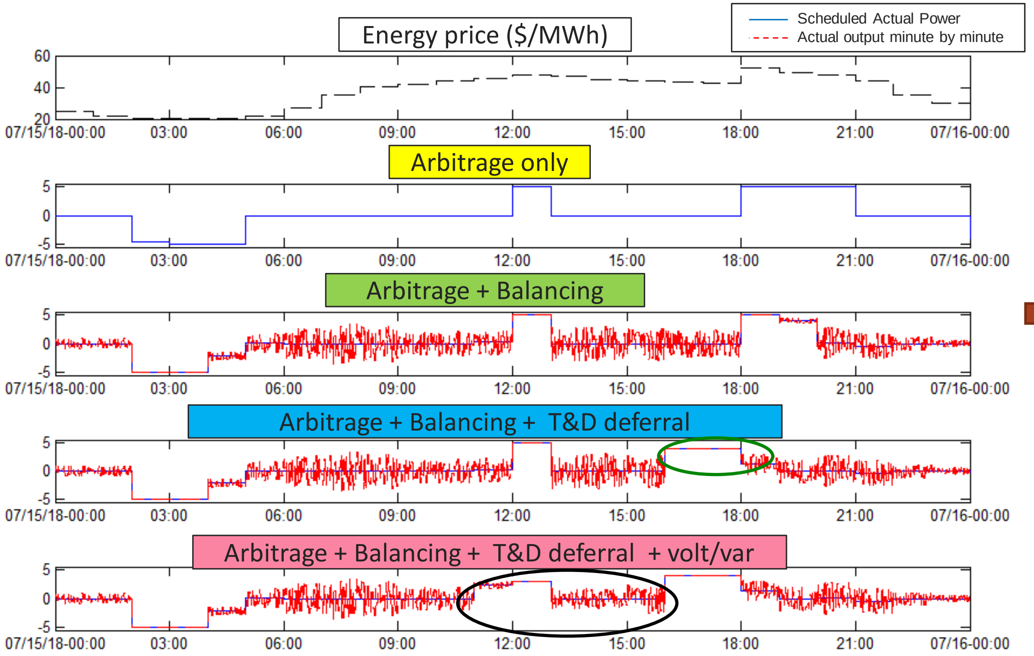
n = Number of years

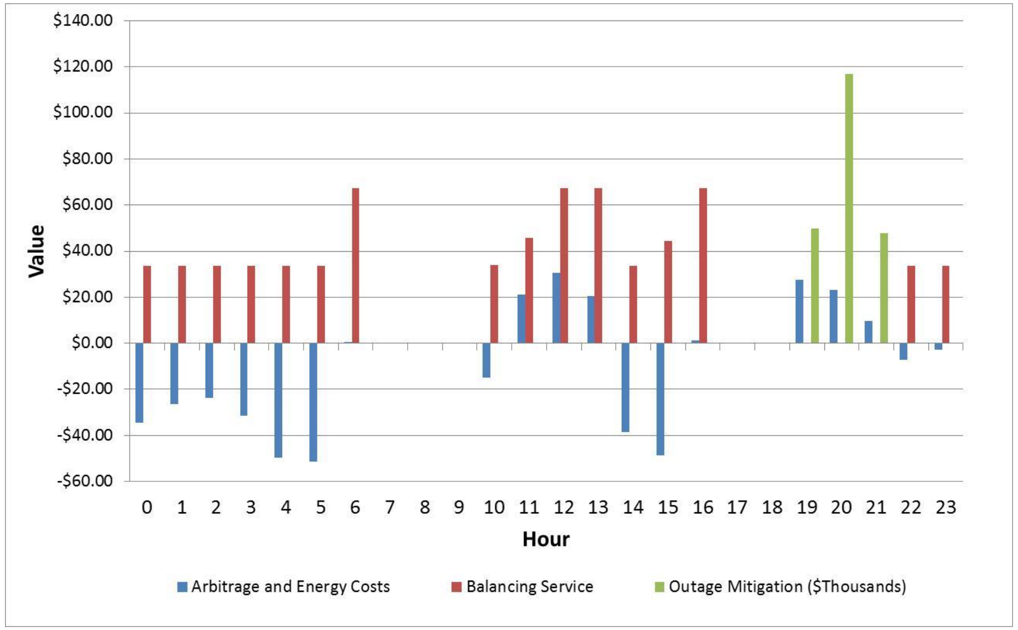
Assuming an 8% cost of capital (discount rate) and 3% cost inflation, distribution deferral of six years for a $10 million substation would be valued at $2.5 million based on calculation below:

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



Bundling Services: How To Do It Optimally





Key Lesson: A valuation tool that co-optimizes benefits is required to define technically achievable benefits.

- Multi-dimensional co-optimization procedures required to ensure no double counting of benefits
  - BESSs are energy limited and cannot serve all services simultaneously
  - By using energy in one hour, less is available in the next hour
- Energy storage valuation tools are required

(1) Portland General Electric (PGE) Salem Smart Power Center (SSPC)

- Developed as an R&D project under the Pacific Northwest Smart Grid Demo as part of the American Recovery and Reinvestment Act of 2009
- The U.S. Department of Energy (DOE) provided half of the funding
- 5 MW – 1.25 MWh lithium-ion battery system built and managed by PGE

- Potential energy storage benefits:
  - Energy arbitrage
  - Participation in the Western Energy Imbalance Market (EIM)
  - Demand response
  - Regulation up and down
  - Primary frequency response
  - Spin reserve
  - Non-spin reserve
  - Volt-VAR control
  - Conservation voltage reduction

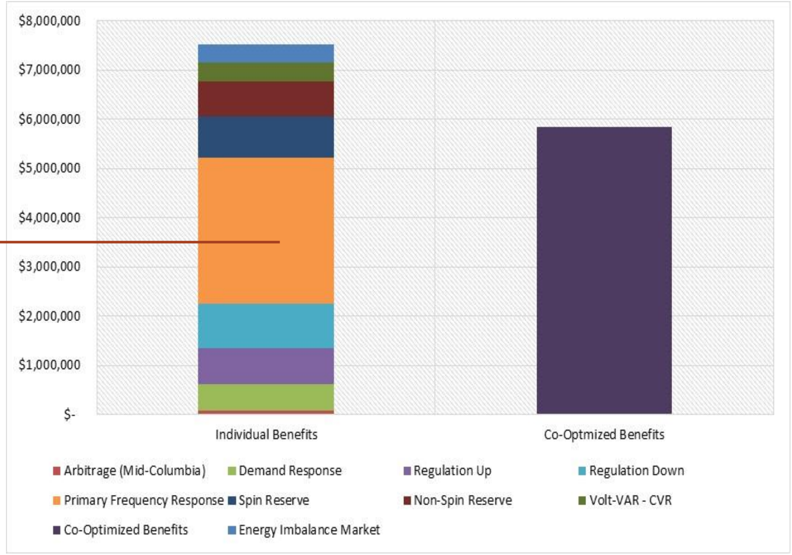
Western Energy Imbalance Market

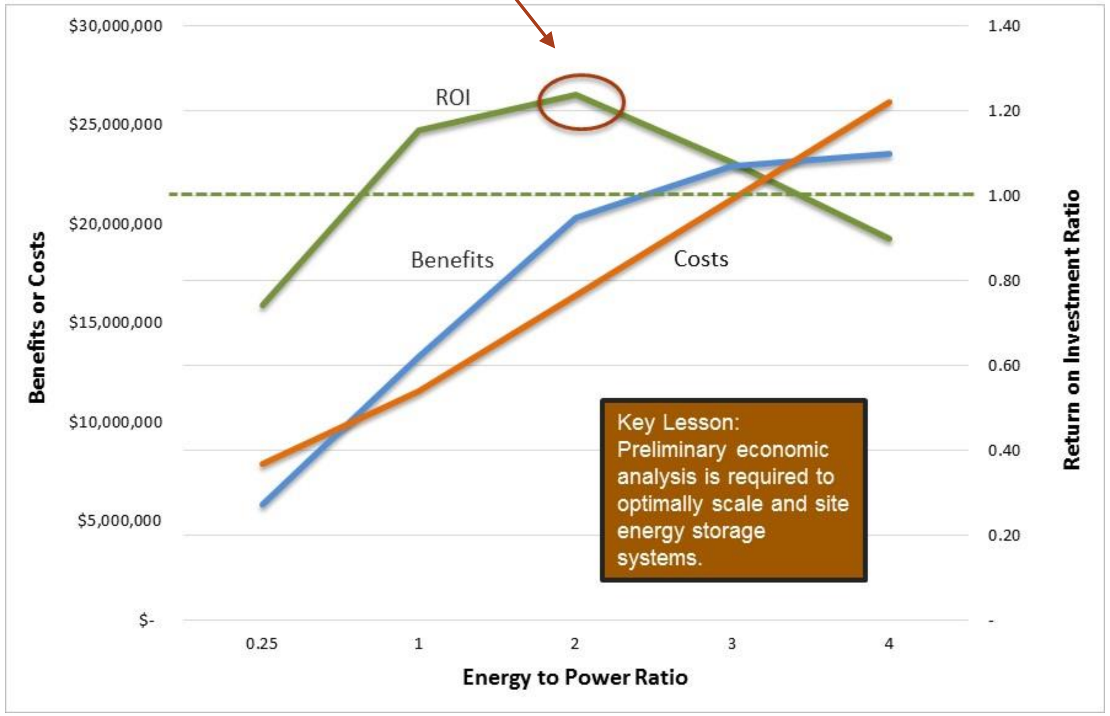
Optimal Scaling of the SPCC

- Evaluated individually the total 20-year value of SSPC operations exceeds $7.5 million in PV terms. When co-optimized, revenue falls to $5.8 million
- At an energy-to-power ratio of 0.25, the SSPC is not well suited to engage in most energy-intensive applications, such as arbitrage and ancillary services, so revenue is lost during the co-optimization process

- By upsizing the energy storage capacity to 10 MWh, the return on investment ratio yields a positive result at 1.24

Technically Unachievable





(2) Nantucket Island Energy Storage System

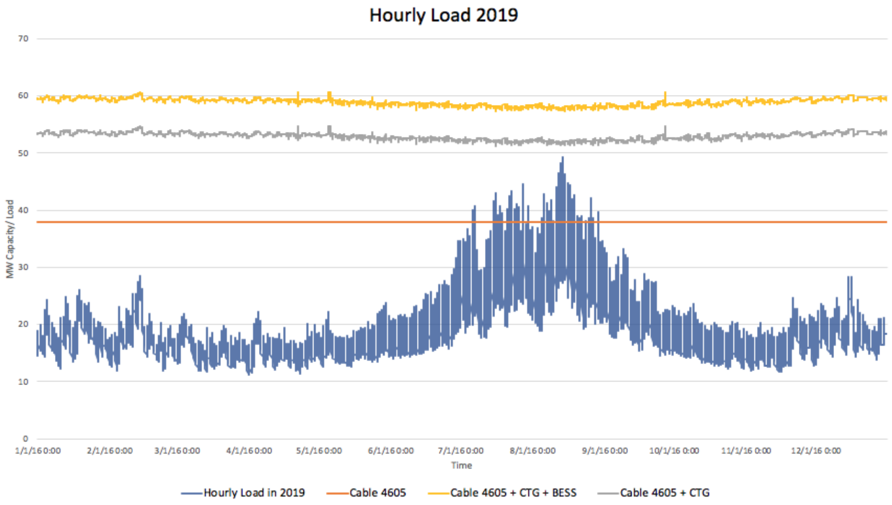
- Nantucket Island located off the coast of Massachusetts
  - Small resident population of 11,000
  - Transmission capacity constraints in summer where population can swell to over 50,000
  - Nantucket Island's electricity supplied by two submarine cables with a combined capacity of 71 megawatts (MW) and two small on-island combustion turbine generators (CTGs) with a combined capacity of 6 MW
  - Rather than deploying a 3rd cable, National Grid is replacing the two CTGs with a single, large CTG with a maximum capacity of 16 MW 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

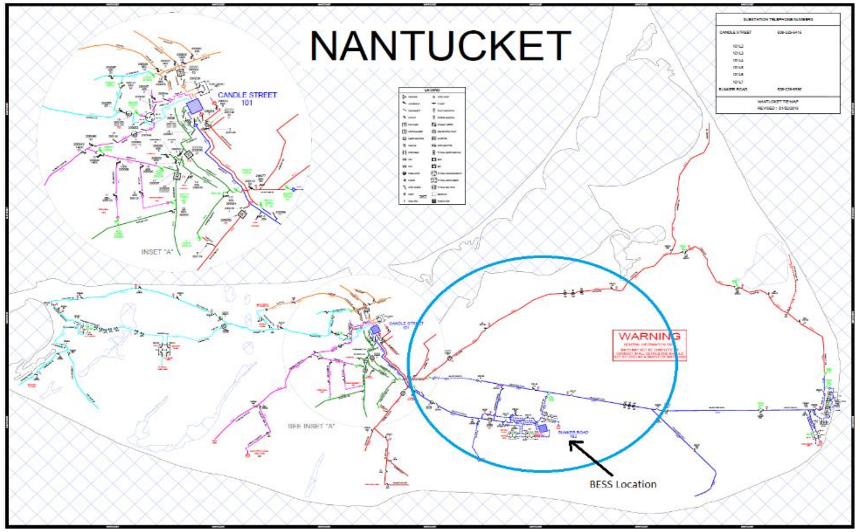
Nantucket, MA

Nantucket Supply Cables

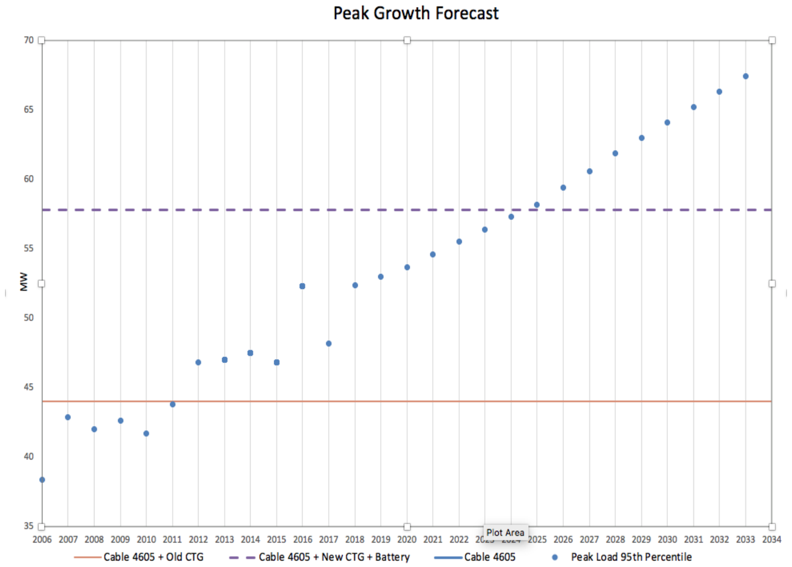
Benefits of Local Operations

- PNNL 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





Modeled Outage on Nantucket Island



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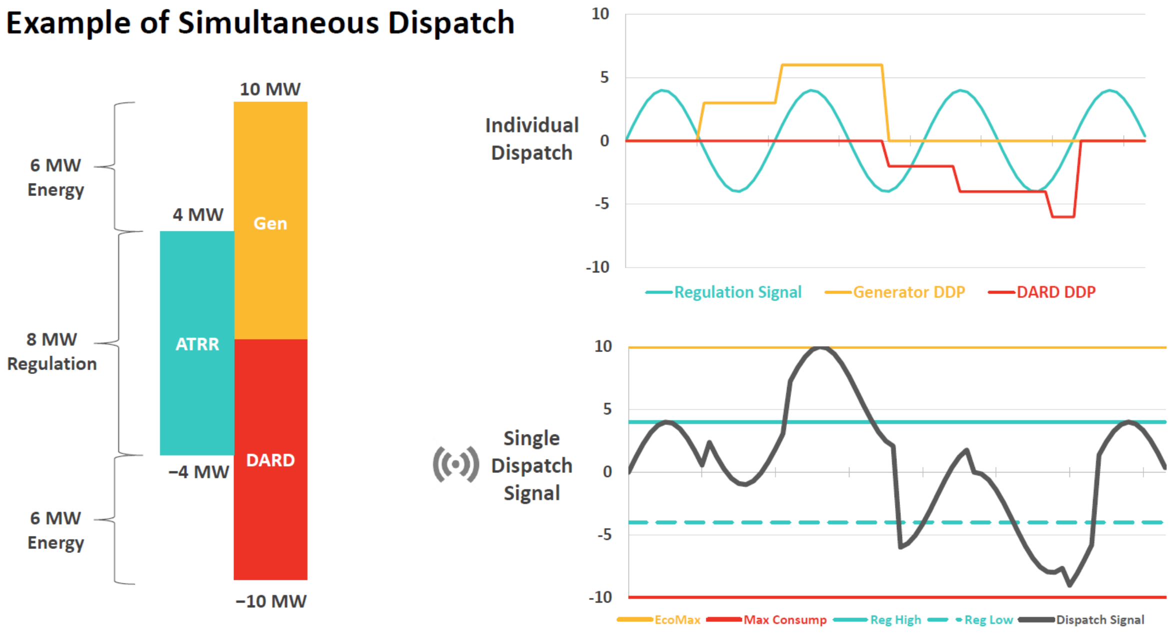
Benefits of Market Operations

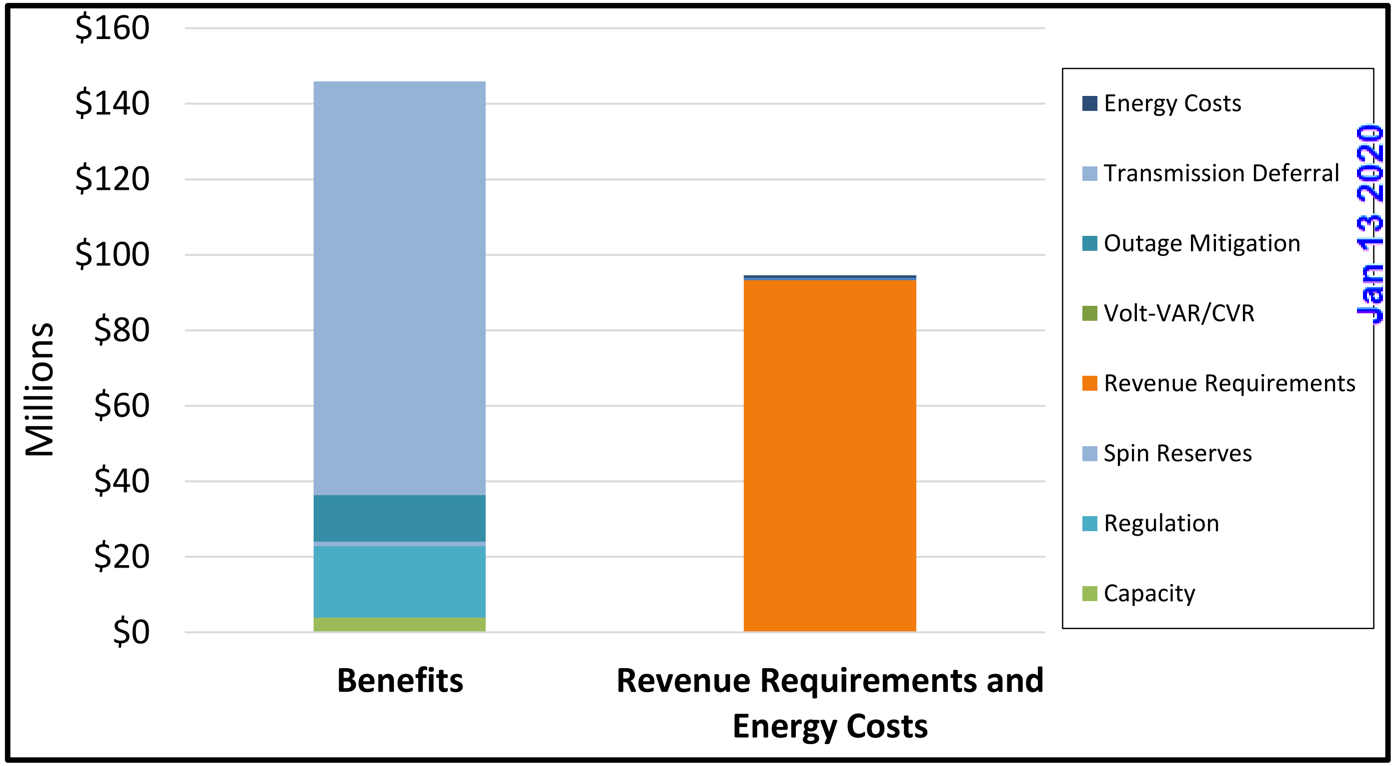
- Nantucket BESS modeled as a continuous storage facility
- Market rules enable National Grid to adjust price bids based on local opportunity costs
- Bid into day-ahead and real-time energy markets using predicted prices while clearing using actual historic price signals – i.e., imperfect foresight
- Regulation follows an energy neutral AGC signal with an assume performance score of 95%
- Market benefits are estimated at $24.0 million over life of BESS; regulation provides $18.8 million (78%) of market benefits, followed by capacity at $4.1 million (17%) and spinning reserves at $1.2 million (5%); energy arbitrage value negligible.



Simultaneous Dispatch of Continuous Storage Facility

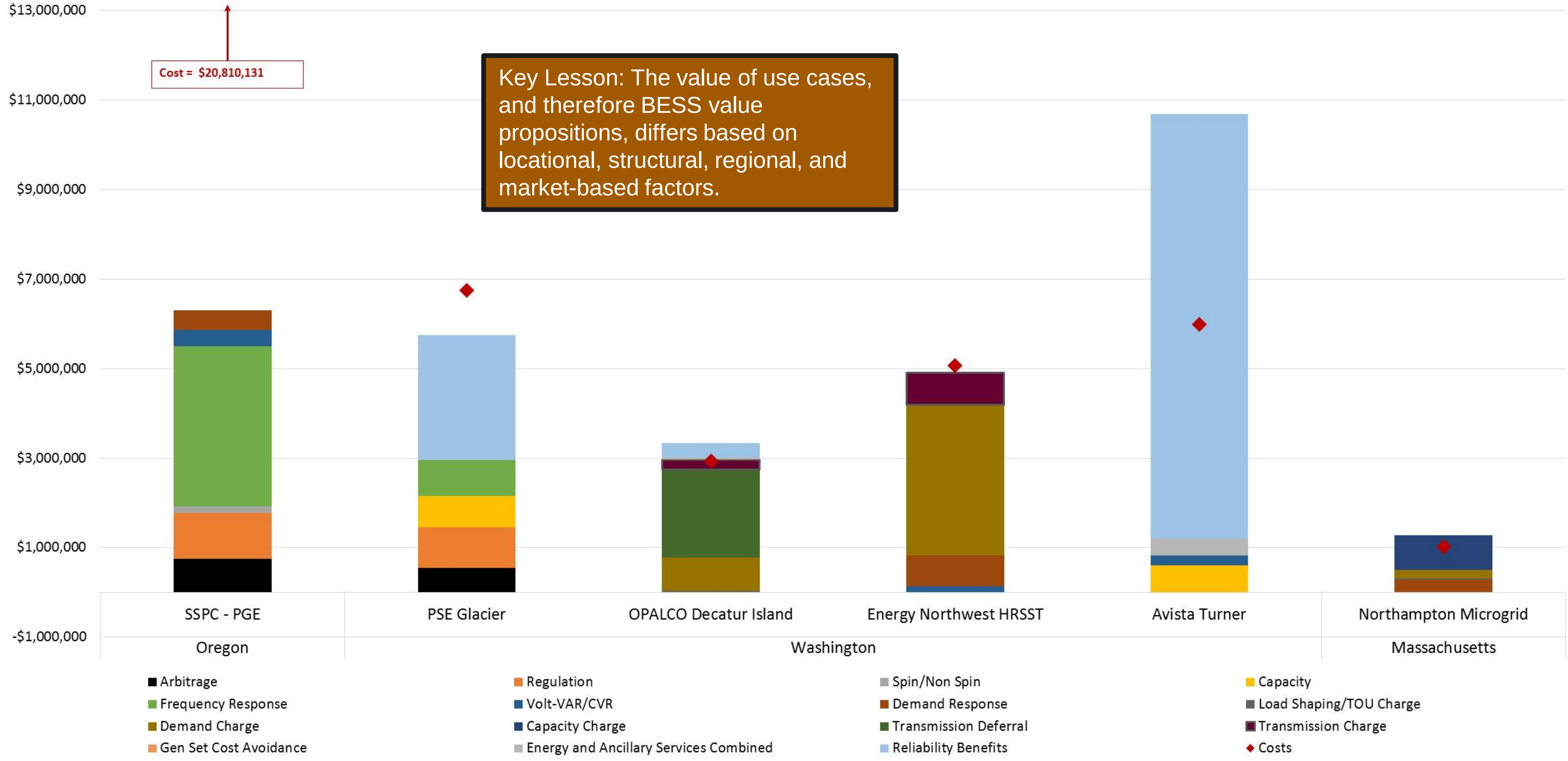
Nantucket Island Conclusions

- The total 20-year present value of BESS and CTG operations at $145.9 million exceeds revenue requirements and energy costs at $93.9 million with a return on investment (ROI) ratio of 1.55
- Benefits are largely driven by the transmission deferral use case, which provides roughly $109 million in PV terms. This is about 75% of the total benefits
- An additional $18.8 million results from regulation services, which comprise 13% of the benefits, making it the second largest benefit stream
- Regulation service dominates the application hours, with the BESS engaged in the provision of this service 7,900 hours each year



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

Results from Several Recent PNNL Economic Assessments of Energy Storage Projects



Key Lesson: The value of use cases, and therefore BESS value propositions, differs based on locational, structural, regional, and market-based factors.

*Reliability benefits are based on assessments of the value of lost load to customers, thus expanding the benefits to include those accruing to both the utility and the customers it serves.

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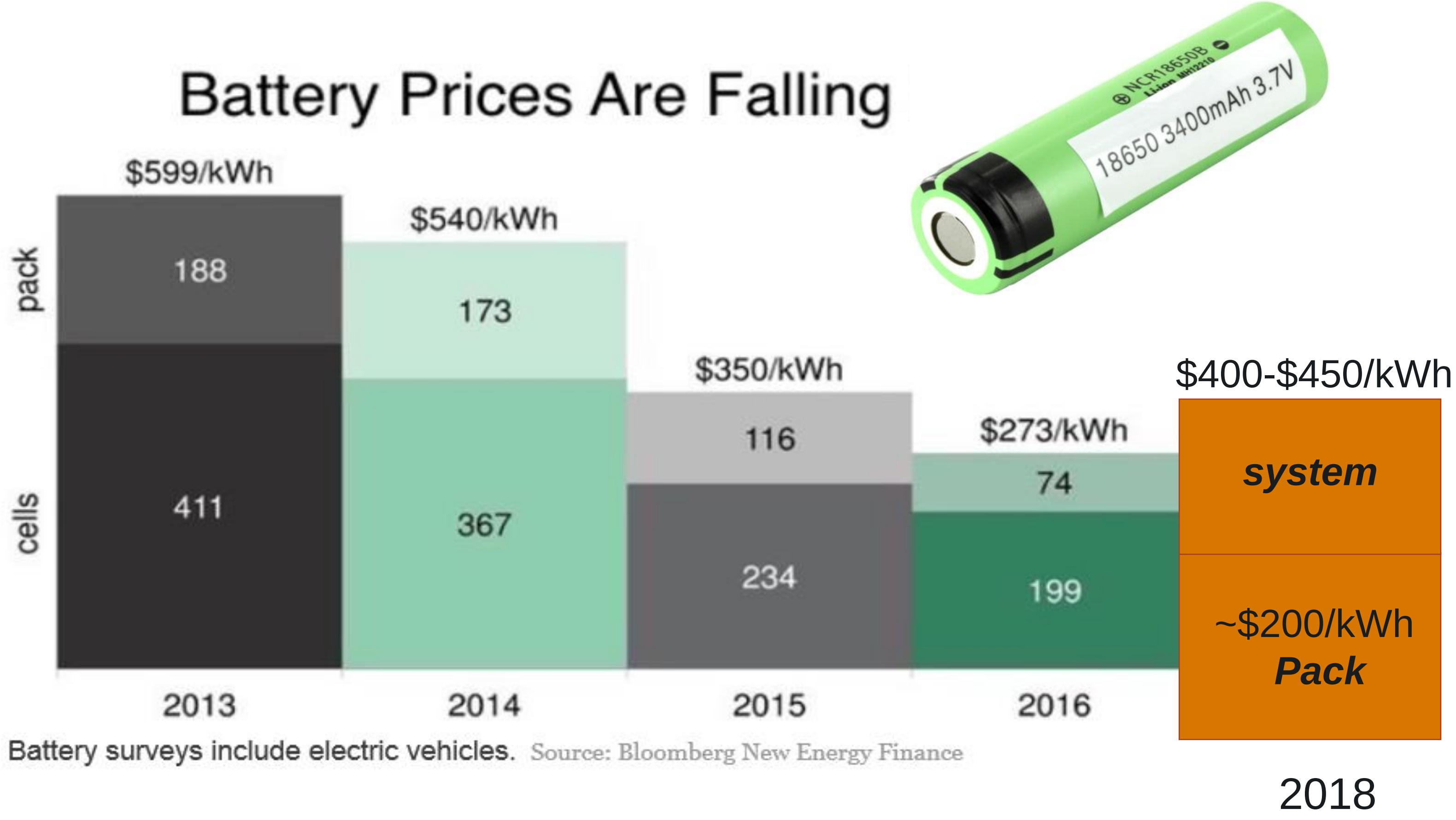
Lithium Ion Battery Prices



Current Cost Estimates - Batteries

Table 4.3. Summary of Compiled Findings by Technology Type – BESS[a]

Parameter	Sodium Sulfur	Li-Ion	Lead Acid	Sodium Metal Halide	Zinc-Hybrid Cathode	Redox Flow
Capital Cost – Energy Capacity ($/kWh)	661 (465)	271 (189)	260 (220)	700 (482)	265 (192)	555 (393)
Power Conversion System ($/kW)	350 (211)	288 (211)	350 (211)	350 (211)	350 (211)	350 (211)
Balance of Plant ($/kW)	100 (95)	100 (95)	100 (95)	100 (95)	100 (95)	100 (95)
Construction and Commission Cost ($/kWh)	133 (127)	101 (96)	176 (167)	115 (110)	173 (164)	190 (180)
Total Project Cost ($/kW)	3,626 (2,674)	1,876 (1,446)	2,194 (1,854)	3,710 (2,674)	2,202 (1,730)	3,430 (2,598)
Total Project Cost ($/kWh)	907 (669)	469 (362)	549 (464)	928 (669)	551 (433)	858 (650)
O&M Fixed ($/kW-yr)	10 (8)	10 (8)	10 (8)	10 (8)	10 (8)	10 (8)
O&M Variable Cents/kWh	0.03	0.03	0.03	0.03	0.03	0.03
System Round-Trip Efficiency (RTE)	0.75	0.86	0.72	0.83	0.72	0.675 (0.7)
Annual RTE Degradation Factor	0.34%	0.50%	5.40%	0.35%	1.50%	0.40%
Response Time (limited by PCS)	1 sec	1 sec	1 sec	1 sec	1 sec	1 sec
Cycles at 80% Depth of Discharge	4,000	3,500	900	3,500	3,500	10,000
Life (Years)	13.5	10	2.6 (3)	12.5	10	15
MRL	9 (10)	9 (10)	9 (10)	7 (9)	6 (8)	8 (9)
TRL	8 (9)	8 (9)	8 (9)	6 (8)	5 (7)	7 (8)

(a) An E/P ratio of 4 hours was used for battery technologies when calculating total costs.
MRL = manufacturing readiness level; O&M = operations and maintenance; TRL = technology readiness level.

Breaks down storage into comparable performance attributes:

- Round-trip efficiency (RTE)
- Lifespan
- Number of cycles
- Degradation rate
- Response time
- Energy to Power ratio (E/P)

Mongird et al, *Energy Storage Technology and Cost Characterization Report*. http://energystorage.pnnl.gov/pdf/PNNL-28866.pdf.

Current Cost Estimates – Pumped Hydro

Parameter	Pumped Storage Hydropower [a]
Capital Cost – Power ($/kW)	2,638[b]
Power Conversion System ($/kW)	Included in Capital Cost
Balance of Plant ($/kW)	
Construction and Commissioning ($/kW)	
Total Project Cost ($/kW)	2,640 [f]
Total Project Cost ($/kWh)	165
Operations and Maintenance (O&M) Fixed ($/kW-year)	15.9
O&M Variable Cents/kWh	0.00025
Round-Trip Efficiency (RTE)	0.8
Annual RTE Degradation Factor	

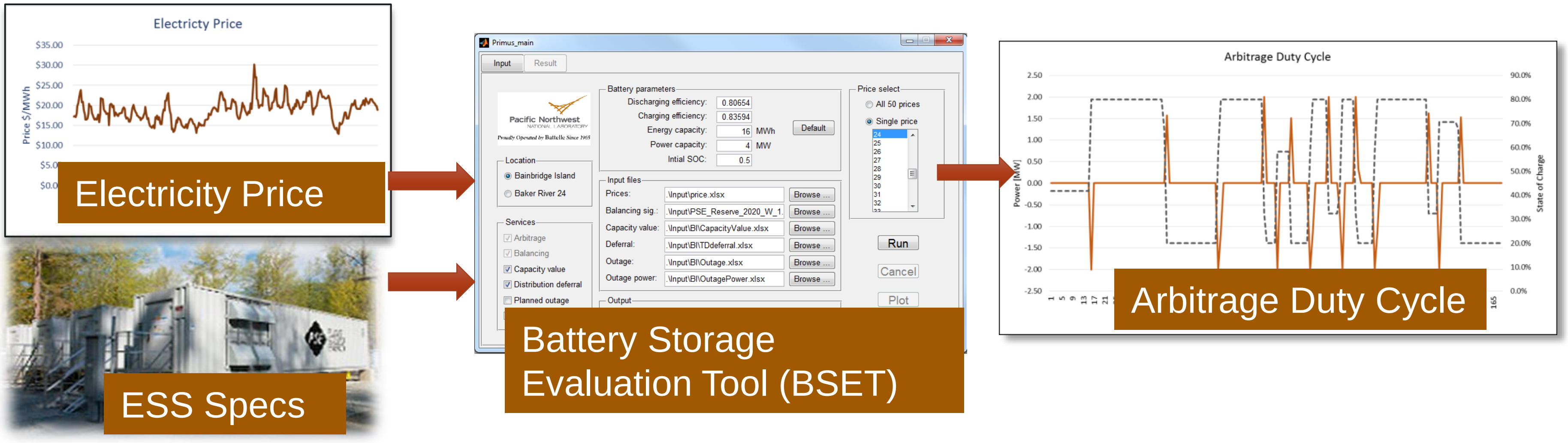
Response Time	FS	AS	Ternary
Spinning-in-air to full-load generation	5-70 s	60 s	20-40 s
Shutdown to full generation	75-120 s	90 s	65-90 s
Spinning-in-air to full load	50-80 s	70 s	25-30 s
Shutdown to full load	160-360 s	230 s	80-85 s
Full load to full generation	90-220 s	280 s	25-60 s
Full generation to full load	240-500 s	470 s	25-45 s[g]

Parameter	Pumped Storage Hydropower [a]
Cycles at 80% Depth of Discharge	15,000
Life (Years)	>25
Manufacturing Readiness Level	9 (10)
Technology Readiness Level	8 (9)

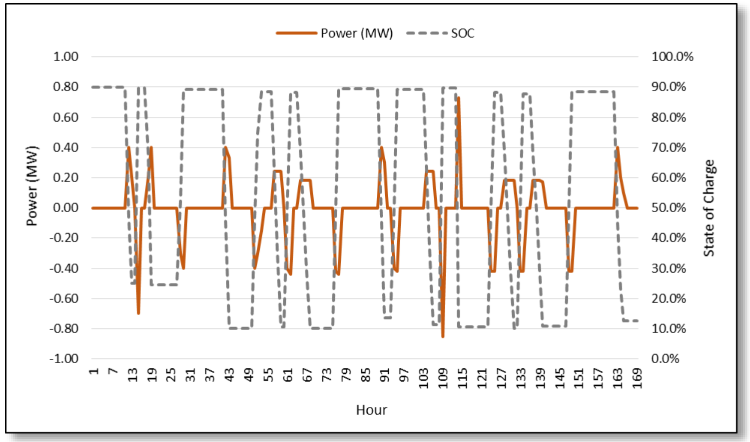
Attributes are not equivalent to selection and do not provide the complete context:

- Scale
- Costs vs. risk
- Speed of response or duration of response
- Commissioning timeframe

Battery Testing at Pacific Northwest National Laboratory



- Battery testing begins with comprehensive test plans and data requirements
- Baseline tests are followed by use case-based tests
- Detailed performance metrics (e.g., round-trip efficiency, response time, ramp rate) established
- Illustrative use case (arbitrage): Maximize revenue from “Buy Low Sell High” transactions based on historical price data



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Overview of Washington Clean Energy Fund (CEF) BESSs

Utility	Site	Chemistry	Rated Power (MW)	Rated Energy (MWh)	Energy-to-Power Ratio (E/P)
Avista	Pullman	All vanadium mixed acid flow	1,000	3,200	3.2
SnoPUD	Everett MESA2	All vanadium mixed acid flow	2,200	8,000	3.6
SnoPUD	Everett MESA1	Lithium-ion LMO & NMC cathodes	2,000	1,000	0.5
PSE	Glacier	LiFePO4	2,000	4,400	2.2

SnoPUD MESA 2

PSE Glacier

SnoPUD MESA1

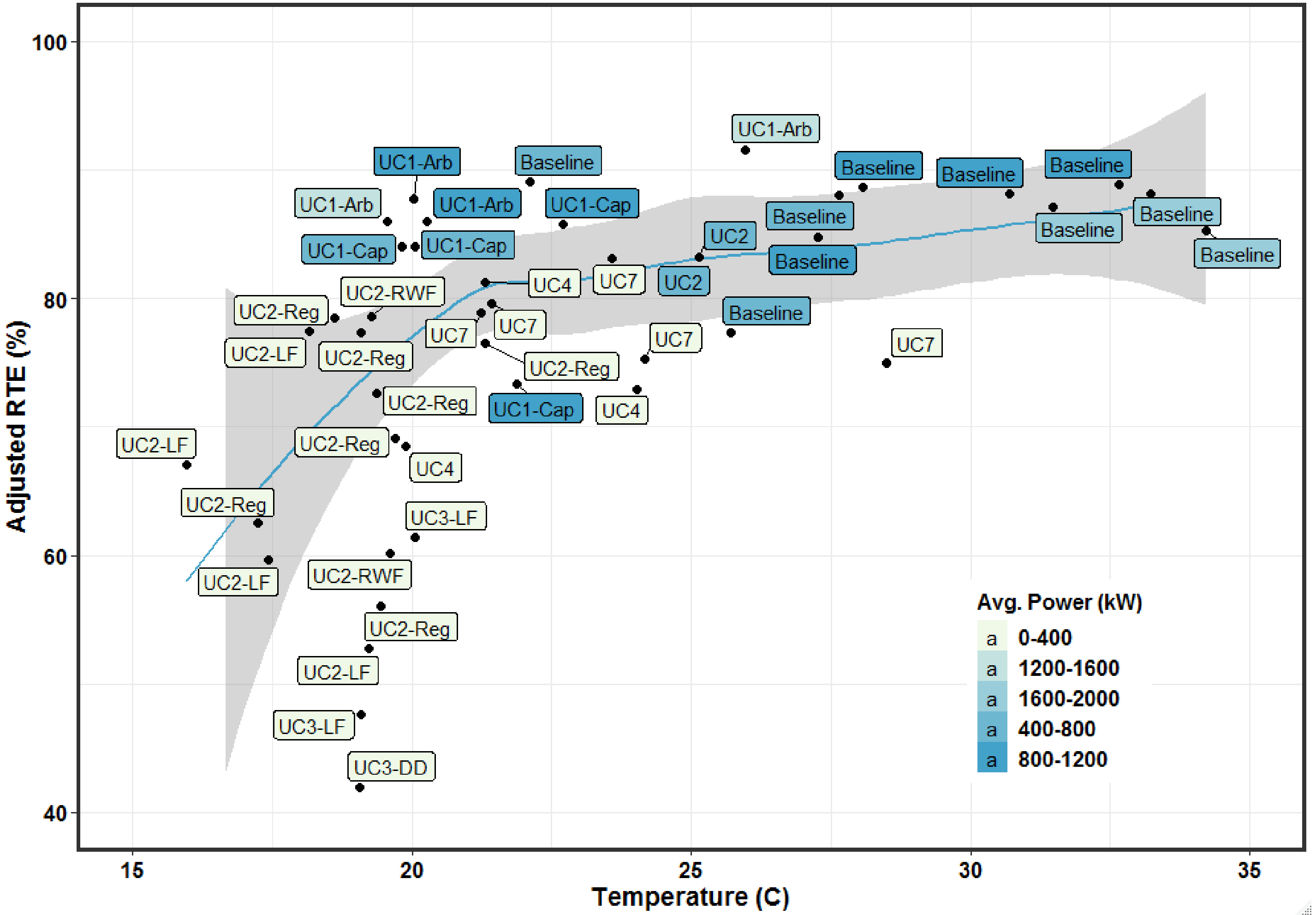
Avista Turner BESS

Battery Round-Trip Efficiency Summary

Battery Type	Low Rate RTE (%)	Low Rate RTE without aux power (%)	Moderate Rate RTE (%)	Moderate Rate RTE without aux power (%)	High Rate RTE (%)	High Rate RTE without aux power (%)
Flow Battery Avista	64	74	64	73	57	63
Flow Battery MESA 2	58	75	60	71	59	68
Lithium-Ion MESA 1	69	82	83	90	77	89
Lithium-Ion PSE Glacier	88	90	83	85	86	88

Lesson: RTE varies significantly among battery technologies (Li-ion vs flow) and even between Li-ion chemistries

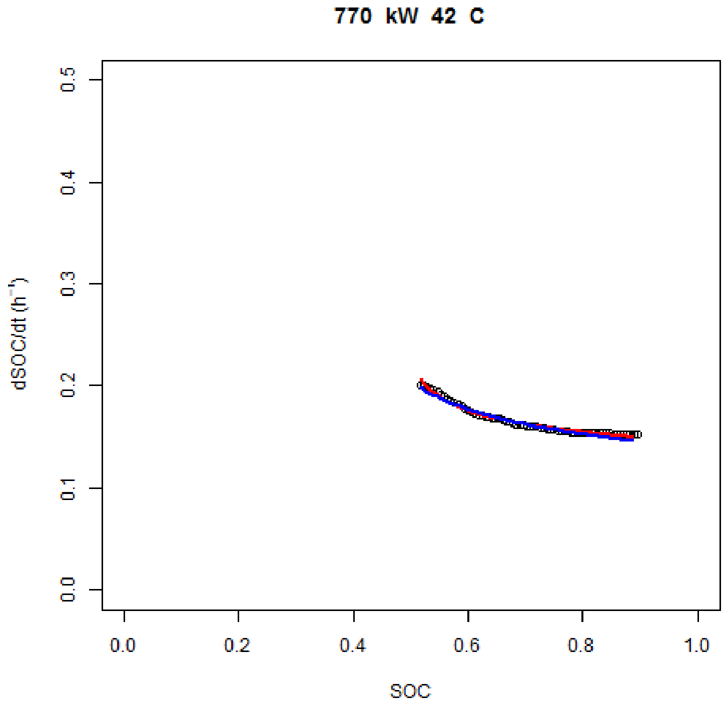
Adjust RTE for Each Duty Cycle (PSE Glacier Li-Ion Battery)



Lesson: The RTE for a single battery can vary significantly based on operating requirements and conditions

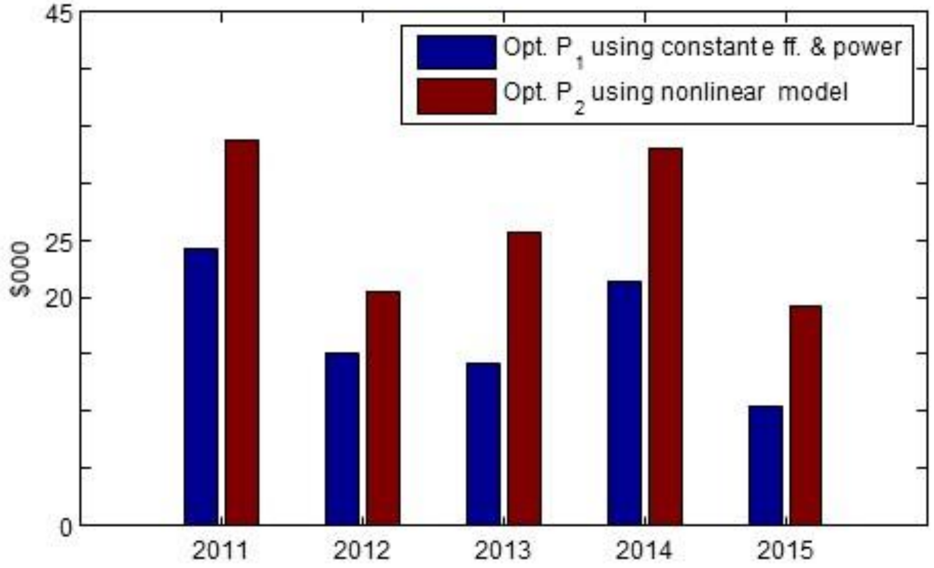
Importance of Operational Knowledge in Defining Value for Energy Storage and Capturing it in Real Time

- Non-linear Performance Modeling
  - Model allows estimation of state of charge (SOC) during operation taking into account 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 BESS owner/operator
  - Self-learning model applicable to energy type of storage system
- State of Health Model
  - Model includes the effect of cycling and calendar aging, taking into account the effect of temperature and voltage
  - Model being verified against data for grid-scale BESSs engaged in field operations



Non-Linear Model Used to Enhance Energy Arbitrage Revenue Opportunity for SnoPUD

Annual estimated benefits in energy arbitrage

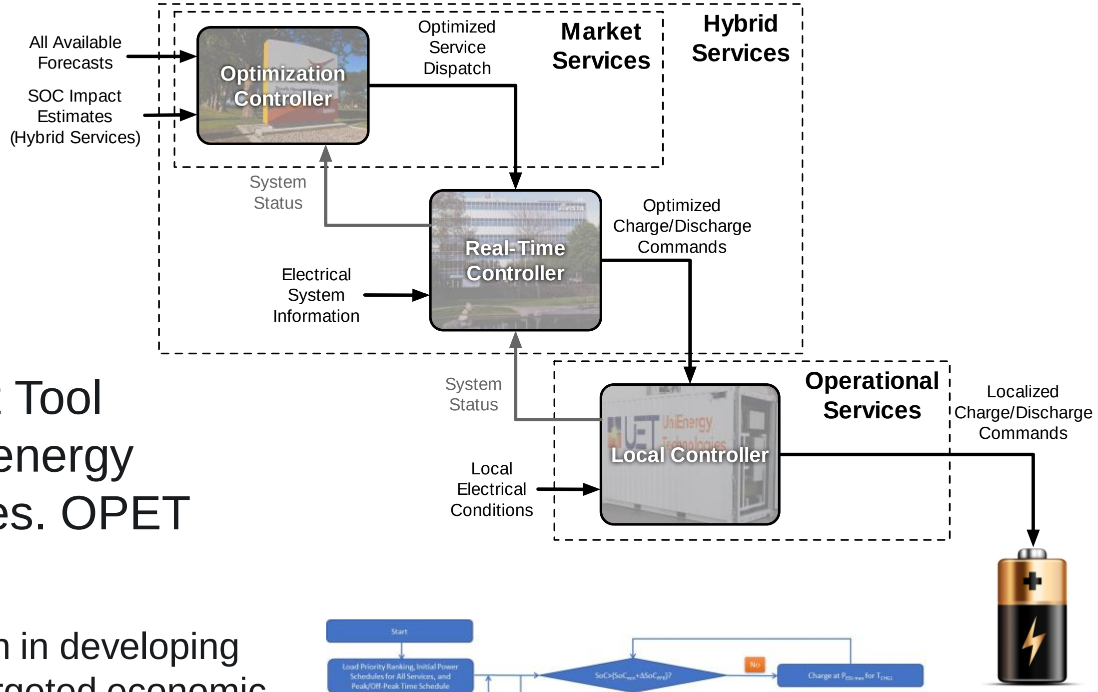


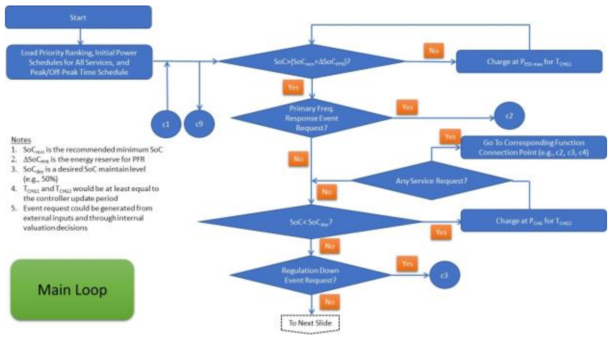
- 50% more arbitrage revenue possible for SnoPUD when optimized using self-learning non-linear battery model
- Battery characterization based on data collected from Avista-operated UET battery deployed in Pullman, WA.

SnoPUD MESA 2
UET 2 MW/8 MWh V/V Flow

Energy Storage Control Algorithms

- Development of control strategies
  - Outline control strategies
  - Develop detailed design of control functions and reporting
  - Simulation/implementation of control functions.
- Optimization Performance Enhancement Tool (OPET): Tool for evaluating commercial energy storage controllers operating at utility sites. OPET goals:
  - Enhance learning of the inputs for consideration in developing storage control strategies that could achieve targeted economic values in real-world situations
  - Enhance performance by finding logic errors in control strategies
  - Evaluate impacts of forecast error on control strategies.

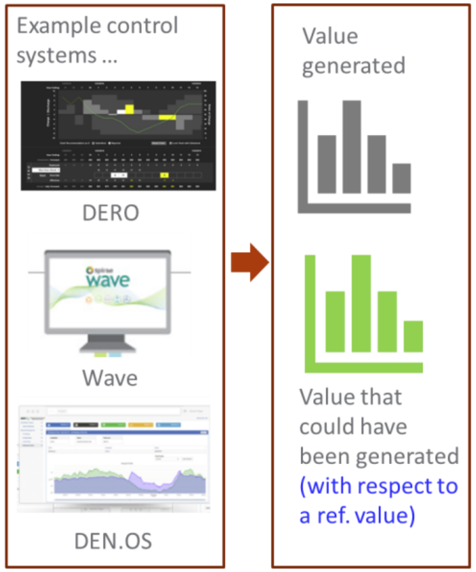




Key Lesson: Development of control strategies is required to obtain value in real-time. We should not compete in developing real-time control systems; rather, we should propel the industry forward through development of advanced algorithms and OPET.

OPET: Concept and Illustrative Results

- ‘Off-the-Shelf’ control systems – generally no dedicated process to keep track of ‘value generated’ vs. ‘value that could have been generated’
- Reasons could be lack of adequate information/approach (logic, prediction error, lack of operational knowledge of BESS)
- Analytics to determine the reasons could help improve the value generated
- Evaluated a utility-installed BESS control system’s (DERO 1.0 at SnoPUD) economic benefit generation performance as a ‘proof-of-concept’
- Use cases considered: Energy Arbitrage (EA), Energy Imbalance (EI), and Co-optimization of EA and EI



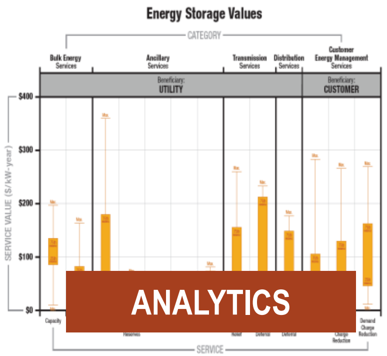
Use Case	DERO	BSET		Improvement Potential	
		BESS Knowledge w/o Foresight	BESS Knowledge with Foresight	BESS Knowledge	Foresight and BESS Knowledge
EA	$72	$203	$272	$131	$200
EI	$134	$156	$204	$22	$70
EA+EI	$224	$1,025	$1,106	$801	$882

Practically more feasible to achieve.

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., PUDs, co-ops, large utilities operating 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 states of charge and battery degradation caused by cycling.

The Future of Energy Storage at Pacific Northwest National Laboratory



- Expanding models to include non-battery storage, including pumped storage hydro and power-to-gas
- Industry standard valuation model in collaboration with other national laboratories and industry groups
- Tools for defining market penetration of storage by region at various cost targets
- Expanded distribution system integration, performance characterization, and control systems capabilities
- Optimal siting/sizing of energy storage in balancing areas

- Increase the performance, safety, and reliability of grid-scale storage
- Reduce costs of energy storage technologies
- Accelerate design, prototype, and testing of new grid-scale batteries
- Provide independent validation of the lifetime and performance of new technologies

- Removing market and regulatory barriers to energy storage adoption; (projects with HI, NV, OR, and WA)
- Industry-accepted integrated resource planning model
- Expand and raise profile of the DOE Energy Storage Policy Database
- Develop valuation handbook

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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

Q/A and Further Information

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