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Results from the Washington State Clean Energy Fund Analytics Program

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DISCOVERY
in Action

U.S. DEPARTMENT OF
ENERGY

Energy Storage Holds Tremendous Value

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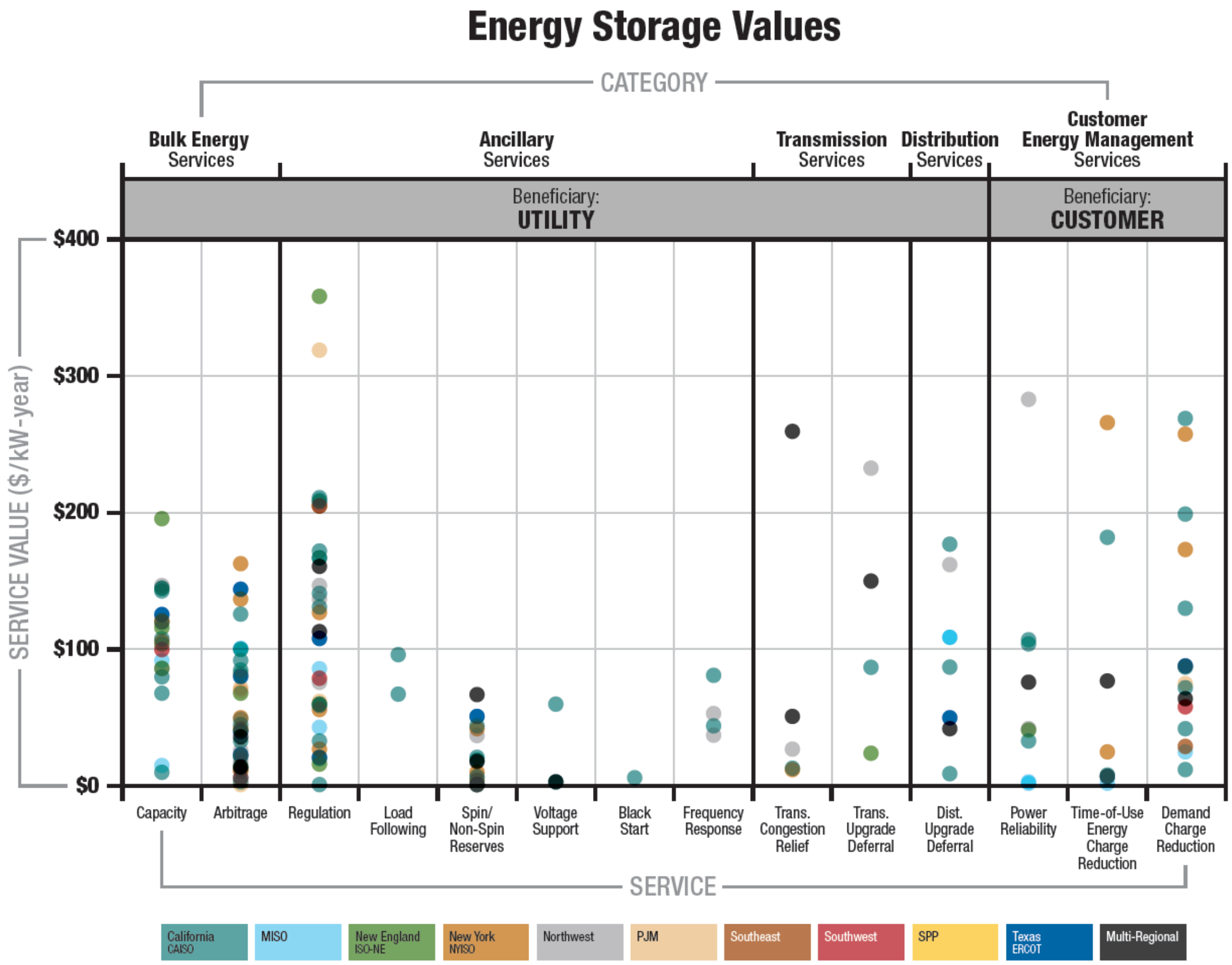

Key Lesson: The value of distributed energy resources accrue at multiple levels of the electric grid.

Washington Clean Energy Fund (CEF) Energy Storage Analytics Program Synopsis

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Objective

- Provide a framework for evaluating the technical and financial benefits of energy storage, and exploring the value that energy storage can deliver to Washington utilities and the customers they serve.

Phases

Phase 1: **Data and Data Systems** → ***Phase 2: Use Cases / Performance Monitoring*** → ***Phase 3:*** **Evaluation**

1) Develop Data Requirements and Data Systems
2) Install Energy Storage Systems (ESS), Run Use Cases, and Document Technical Performance
3) Evaluate Technical and Financial Performance

Team

- **PNNL:** Brings expertise in energy/economics/environment system analysis and modeling
- **PSE, SnoPUD, and Avista:** Bring deep operational experience and required utility data / test sites
- **Washington Dept. of Commerce**: Program management

Department of Commerce
Innovation is in our nature.

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AVISTA

PSE PUGET SOUND ENERGY

SNOHOMISH COUNTY PUD PUBLIC UTILITY DISTRICT NO. 1

Washington State CEF 1 Energy Storage Projects

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SNOHOMISH COUNTY PUD PUBLIC UTILITY DISTRICT NO. 1

PSE PUGET SOUND ENERGY

2 MW / 4.4 MWh lithium-ion/phosphate battery – Glacier, WA

2MW / 1 MWh Li-ion system
2MW, 8.8 MWh UET vanadium-flow - Everett, WA

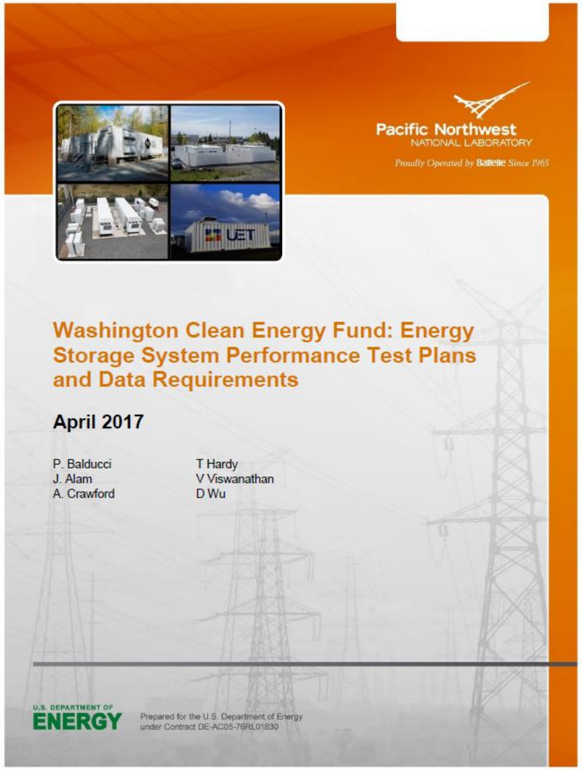
AVISTA

1 MW / 3.2 MWh UET vanadium-flow battery – Pullman, WA

Total – 7 MW / 15 MWh; $14.3 million state investment / $43 million total investment for energy storage systems

Battery Testing Begins with Comprehensive Test Plan and Data Requirements

- Baseline tests
  - Stored energy capacity
  - Response time and ramp rate
  - Internal resistance
  - Peak shaving
  - Frequency regulation
- Use-case based duty cycles specific to each utility and battery system; detailed duty cycle tables in appendices
- Critical and optional AC- and DC-side data requirements specified by time increments
- Detailed performance metrics



CEF Use Case Duty Cycle Types

- Time Series Based:
  - Exact charge/discharge commands are provided with respect to time.
  - Determined based on historical time series data (e.g. Electricity price).
  - Day-of-week and time-of-day matching necessary.
- Set-point Based:
  - A set-point is provided and the ESS active/reactive power output is controlled based on the set-point.
- Others: tests conducted by utility using their own test plan

Use Case and application as described in PNNL Catalog
UC1: Energy Shifting
Energy shifting from peak to off-peak on a daily basis
System capacity to meet adequacy requirements
UC2: Provide Grid Flexibility
Regulation services
Load following services
Real-world flexibility operation
UC3: Improving Distribution Systems Efficiency
Volt/Var control with local and/or remote information
Load-shaping service
Deferment of distribution system upgrade
UC4: Outage Management of Critical Loads
UC5: Enhanced Voltage Control
Volt/Var control with local and/or remote information and during enhanced CVR events
UC6: Grid-connected and islanded micro-grid operations
Black Start operation
Micro-grid operation while grid-connected
Micro-grid operation in islanded mode

Time series Condition based Others

UC1: Arbitrage and System Capacity to Meet Adequacy Requirement

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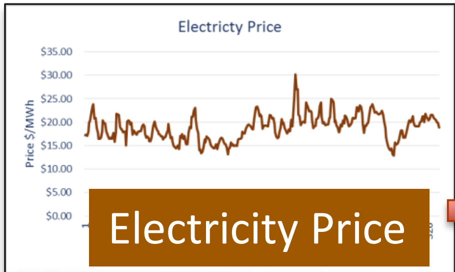
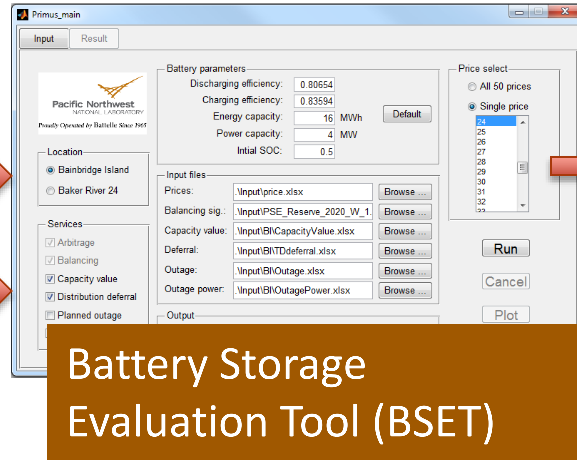
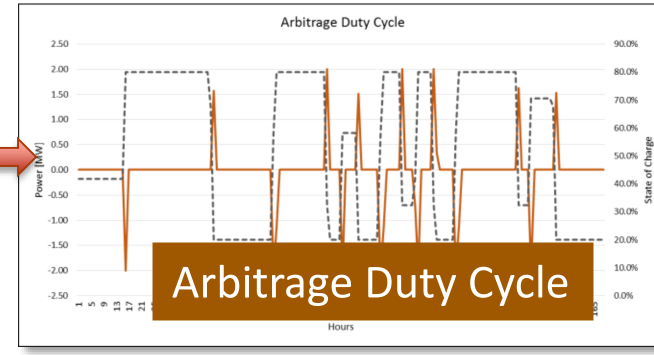
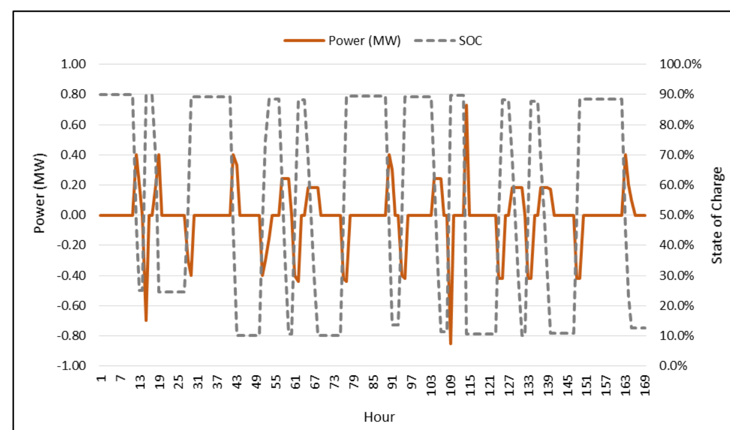






- Arbitrage: Maximize revenue from “Buy Low Sell High” transactions based on historical price data

- System Capacity:
  - Peak-Shaving support during system wide peak
  - Capacity triggers: different for each utility
  - 1-4 hours of discharge periods



Arbitrage Use Case Testing FBESS

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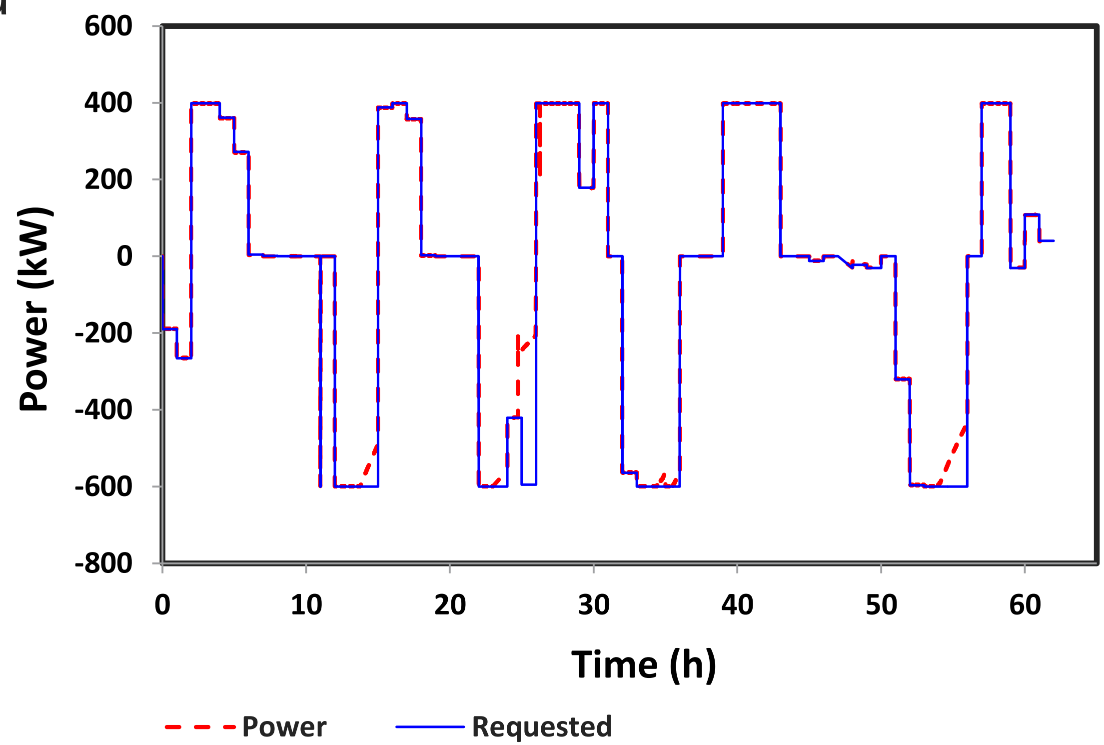
Date	RTE	RTE No Aux	Charge Power (kW)	Discharge Power (kw)	Strings Active
2016/01/20 02:00:00	74%	83%	600	520	2
2016/01/25 04:00:00	73%	82%	600	400	2
2016/01/26 04:00:00	74%	84%	600	400	2
2016/01/22 02:00:00	68%	78%	600	400	2
2016/01/19 18:00:00	67%	76%	600	520	2

Key Lesson: Battery performance varies considerably by manufacturer and chemistry.

- Discharging at 520 kW and 400 kW changes duration of ESS to 6 and 8 hours, respectively
- Modeled energy schedule based on historic data and applied to battery system
- Variation in RTE may be due to:
  - Change in initial SOC
  - Change in temperature



Challenges and Lessons

- Keeping day and time correspondence between duty cycles and actual tests.
- Managing duty cycles for interrupted or failed tests.

Careful selection of data for duty cycle keeping headroom for change in plan/interruptions.

- Duty cycles producing unexplainable/unacceptable test results.

Understanding of actual system behavior/parameter from test results and reflecting in the duty cycle.

Background on Battery Performance

- Flow Battery Energy Storage Systems (FBESS) performance depends on various factors
  - Operating mode – charge or discharge
  - Power
  - State of charge (SOC)
  - State of health (SOH)
  - Operating temperature
- FBESS rating can be confusing
  - 1MW, 3.2 MWh is FBESS rating
  - However, at 1 MW, the energy obtained is ~ 2 MWh
  - To obtain the rated 3.2 MWh energy, the discharge power must be 520 kW
- For the Li-ion battery system tested (MESA-1 at SnoPUD), the 2 MW / 1 MWh rating is a bit more representative of performance
- Need to predict battery performance at various SOCs under different operating conditions
  - Battery SOC calculated by accounting for efficiency losses during charge and discharge

Challenges of Conventional Approach

- BSET model used one number for round trip efficiency (RTE)
  - Use square root of RTE to estimate one way efficiency
  - Use one way efficiency to estimate delta SOC
- In real systems, the efficiency depends on
  - Operating mode – charge or discharge
  - Power
  - SOC
  - Temperature
  - SOH
- Hence, the BSET approach was overly simplistic.

Data Collected - UET Flow Battery Energy Storage System (FBESS)

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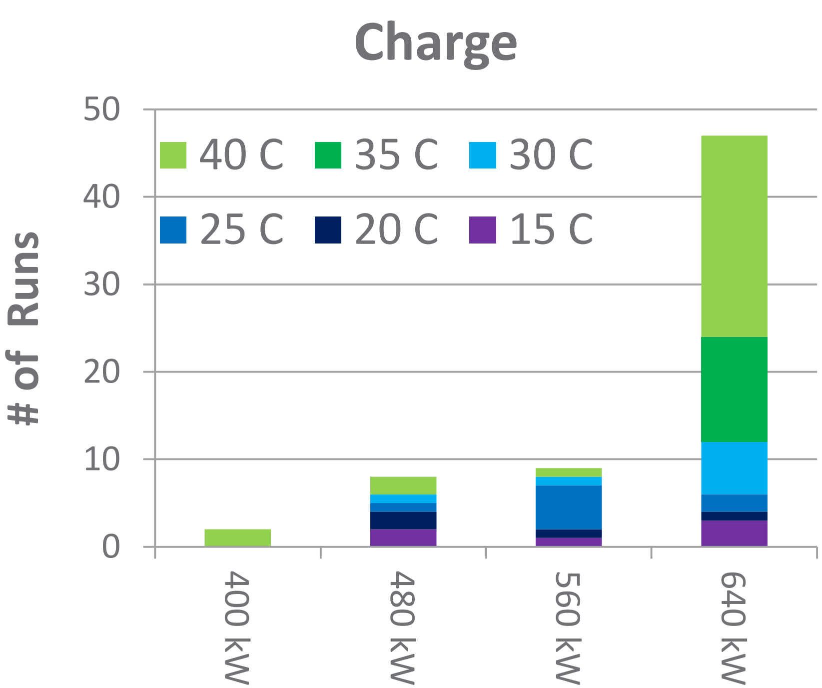
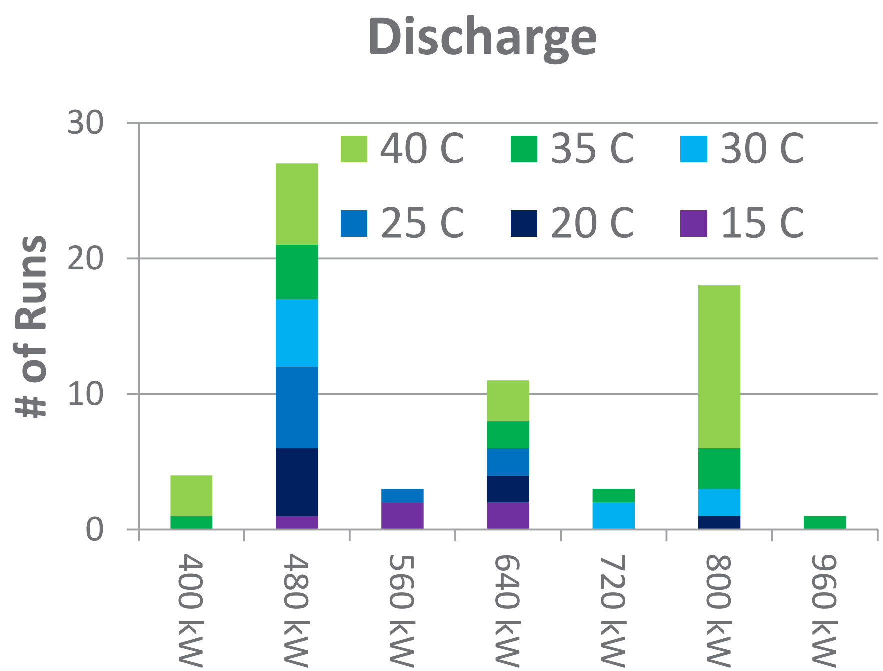
- After grouping data into charge and discharge periods, for purposes of building a model we want to select the highest quality data – therefore periods in which power is constant over an SOC range of >30% are chosen.
- This corresponds to 66 charges and 67 discharges at various powers and temperatures.





Curve Modeling

- Derivative of SOC with respect to time is taken of smoothed data, and plotted as function of SOC
- This is done for each charge or discharge period
- Each is modeled well by the following equation:

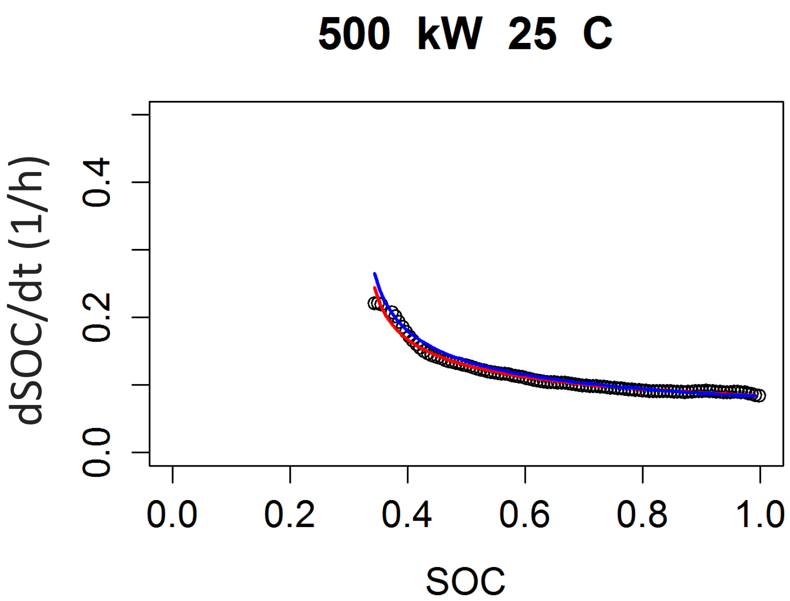
$$\frac{dSOC}{dt} = a(SOC - b)^c$$

$$a = P\left(K + K_p P + K_T T\right)$$

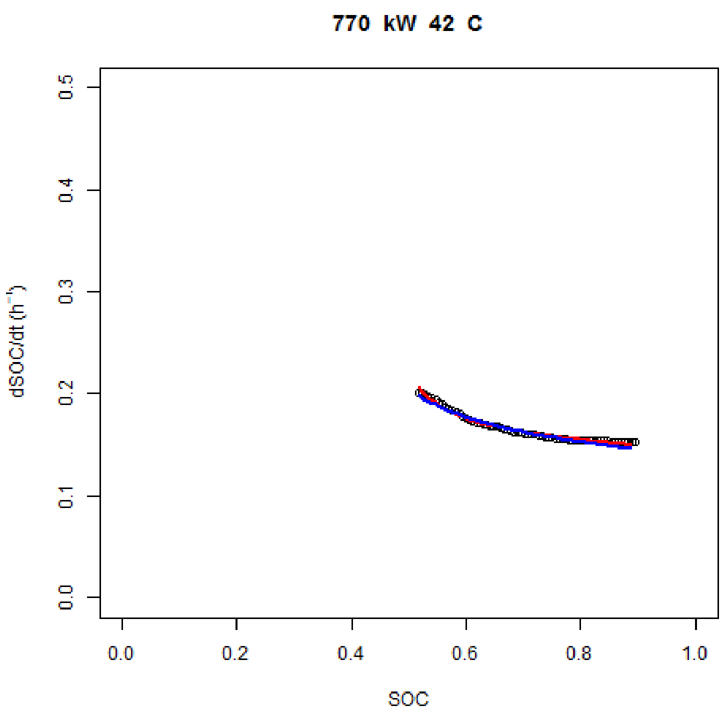
$$b = P\left(K + K_p P + K_T T\right)$$

$$c = K + K_p P + K_T T$$

- Each curve has constants a, b, c automatically fit (see red line)
- These fits are automatically collected into a database so there is one associated with each charge and discharge period.



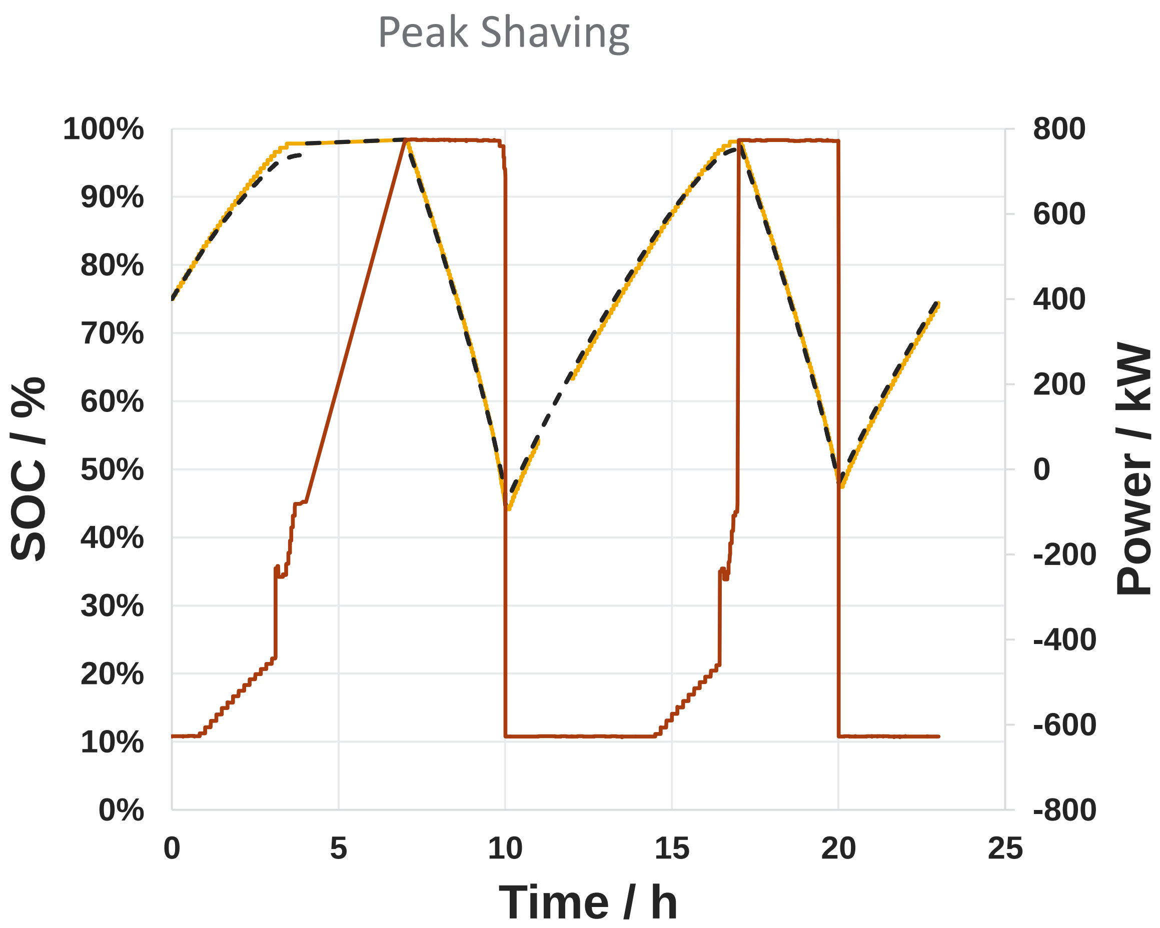
Model Validation



- The fit is shown for each discharge curve
- Black dots show actual smoothed derivative from data
- Red line is the best fit to this specific dataset
- Blue line is the global model where parameters are calculated using the power and temperature of this dataset.

Validation Example

- Model accurately estimates change in SOC during charge and discharge
- Slightly underestimates rate of SOC increase for low charge rates – need more data on low charge rates.



Non-Linear Battery Model Summary

- Model allows estimation of SOC during operation taking into account
  - Operating mode
  - Power
  - SOC
  - Temperature
- Model has been validated with data
- Allows calculation of one way efficiency from rate of change of SOC
- 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
- Model will be fine tuned as more data gathered.

Battery Performance Round Trip Efficiency Summary

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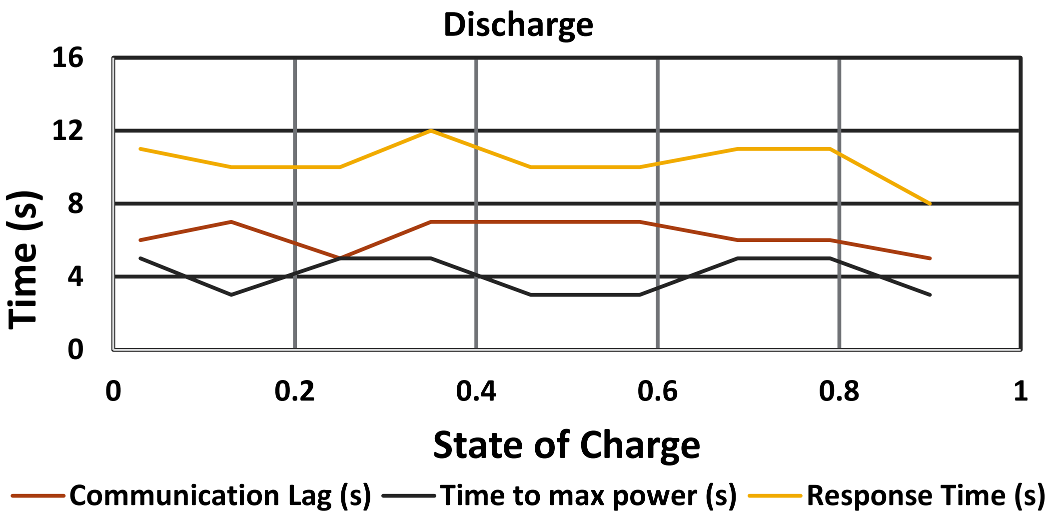
	Low Rate		Moderate Rate		High Rate	
	RTE (%)	RTE without aux power (%)	RTE (%)	RTE without aux power (%)	RTE	RTE without aux power (%)
Flow Battery	64.2	71	58.9	64.2	57.6	62.6
Lithium-Ion MESA 1	66.9	82.7	83.0	90.9	79.4	87.9
Lithium-Ion Puget Sound Energy (PSE) Glacier	87.3	89.5	86.5	88.7	85.8	87.1

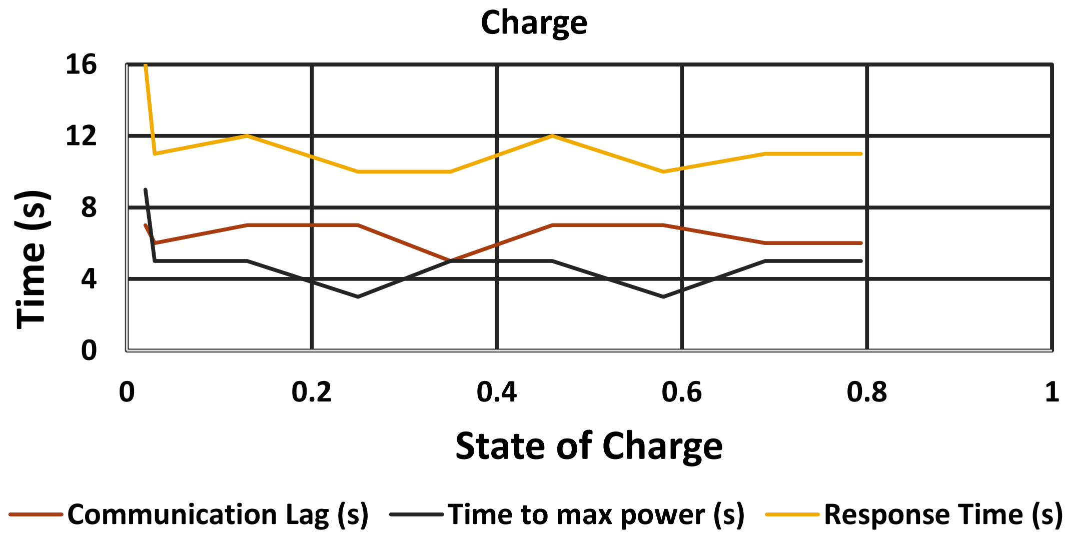
Avista FBESS Signal Tracking and Response Time

Metric	With Aux	Without Aux
Root mean square error (RMSE) as % of rated power	3.2	2.6
Normalized RMSE as % of average of absolute value of the signal	12.0	9.5
Mean Absolute Error of Signal (kW)	14.9	7.3
Mean Absolute Error in Energy (kWh)	299.6	7.3
Percent signal tracked for deviation		
< 1% of signal	53.2	67.8
< 10% of signal	73.0	86.0
< 2% of rated power	97.9	83.5

- Good signal tracking based on rated power (similar to PSE system)
- Results using deviation <1% and < 10% of signal as criterion similar to PSE system
- Mean absolute error in energy is nearly 0 when auxiliary consumption is ignored
- The BESS reached the rated power in < 1 second, the smallest time interval for which data available

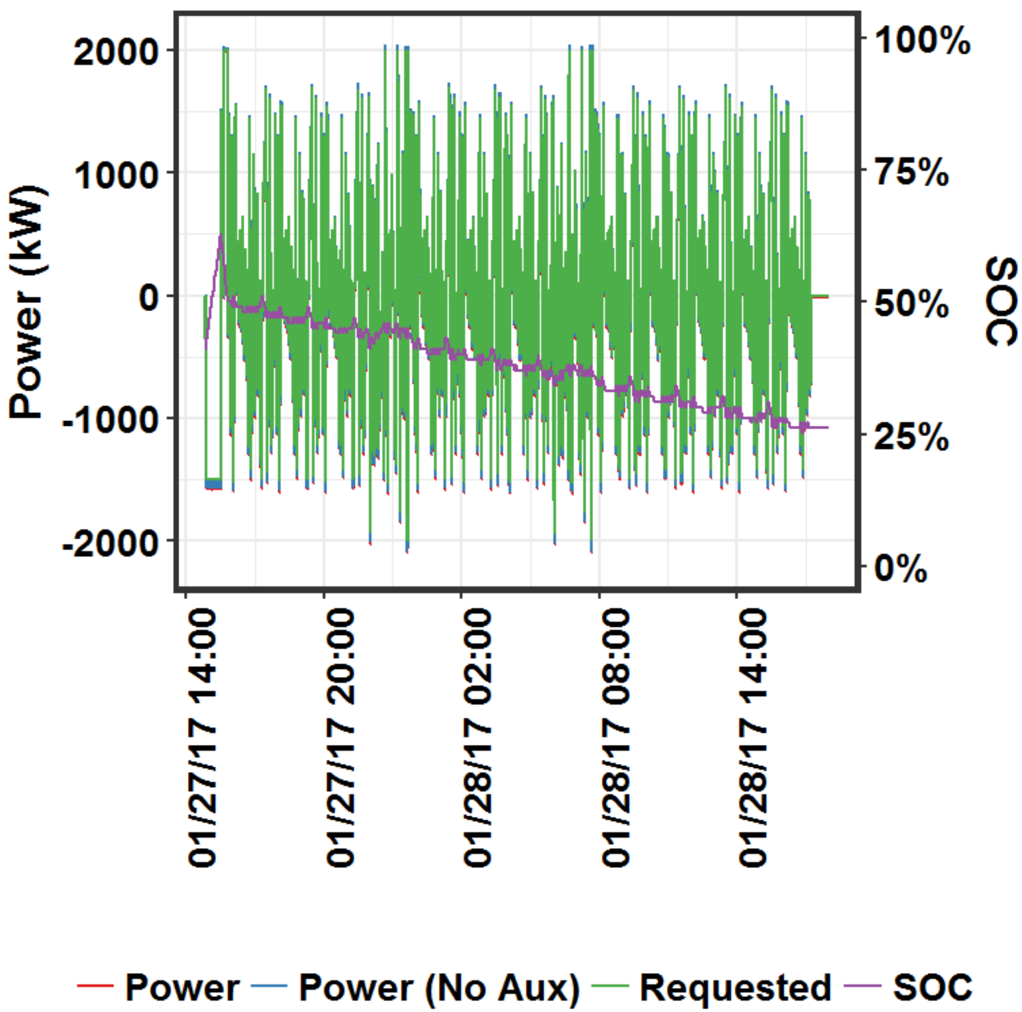
PSE BESS Response Time





- Communication lag of 5-7 seconds
- Time to maximum power 3-5 seconds
- Discharge ramp rates are in the 21 to 38% rated power/second range
- Charge ramp rates are in the 16 to 38% rated power/second range

PSE BESS 2MW/4 MWh Li ion Battery System: UC2 Regulation Services

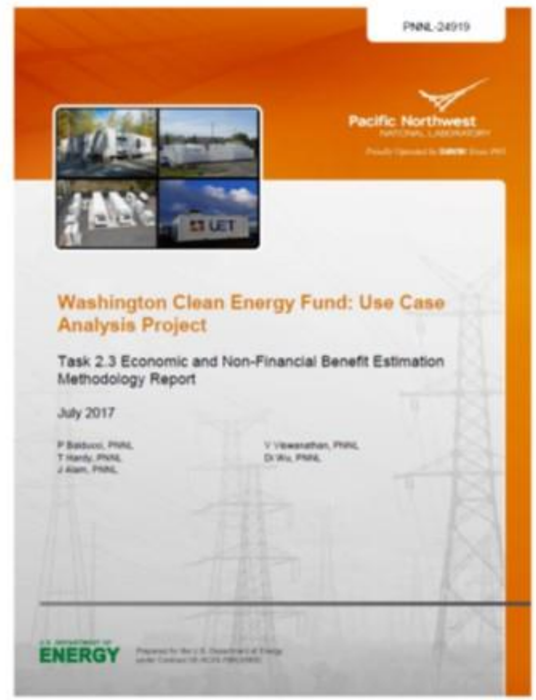


- RTE 74-80%
- RTE w/o aux 76-83%
- Signal tracking 94-98%
- Lower average SOC leads to lower efficiency than Baseline capacity tests

Washington CEF Matrix for Economic Analysis

Use Case	Avista	PSE	Sno-MESA1	Sno-MESA2	Sno-controls Integration
UC1: Energy Shifting					
Energy shifting from peak to off-peak on a daily basis	Y	Y	Y	Y	
System capacity to meet adequacy needs	Y	Y	Y	Y	
UC2: Provide Grid Flexibility					
Regulation services	Y	Y			
Load following services	Y	Y			
Spin / non-spin reserves	Y	Y			
BPA balancing payment minimization			Y	Y	
Real-world flexibility operation	Y	Y			
Primary frequency response	Y	Y			
UC3: Improving Distribution Systems Efficiency					
Volt-VAR control and/or remote information	Y		Y	Y	
Load shaping service	Y				
Deferment of distribution system upgrade	Y				
UC4: Outage Management of Critical Loads		Y			
UC5: Enhanced Voltage Control					
Volt-VAR control with local and/or remote information and during enhanced CVR events	Y				
UC6: Grid-connected and islanded micro-grid operations					
Black start operation	Y				
Micro-grid operation while grid-connected	Y				
Micro-grid operation in islanded mode	Y				
UC7: Optimal Utilization of Energy Storage	Y	Y			Y

- PNNL now collecting required data and modeling systems



Energy Arbitrage

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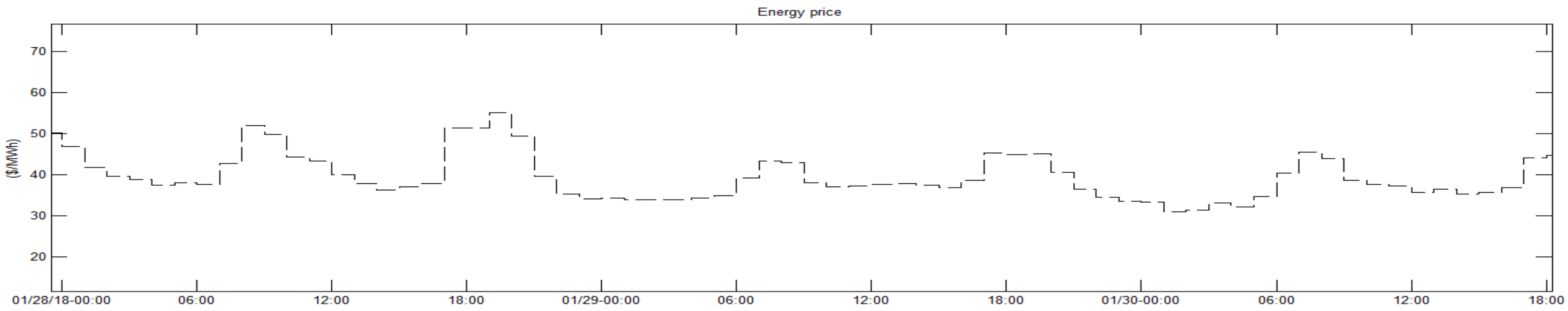
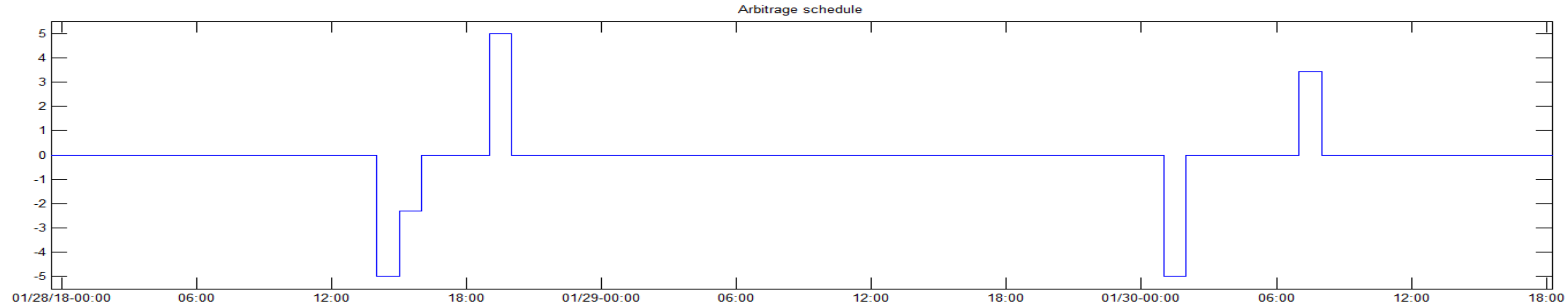
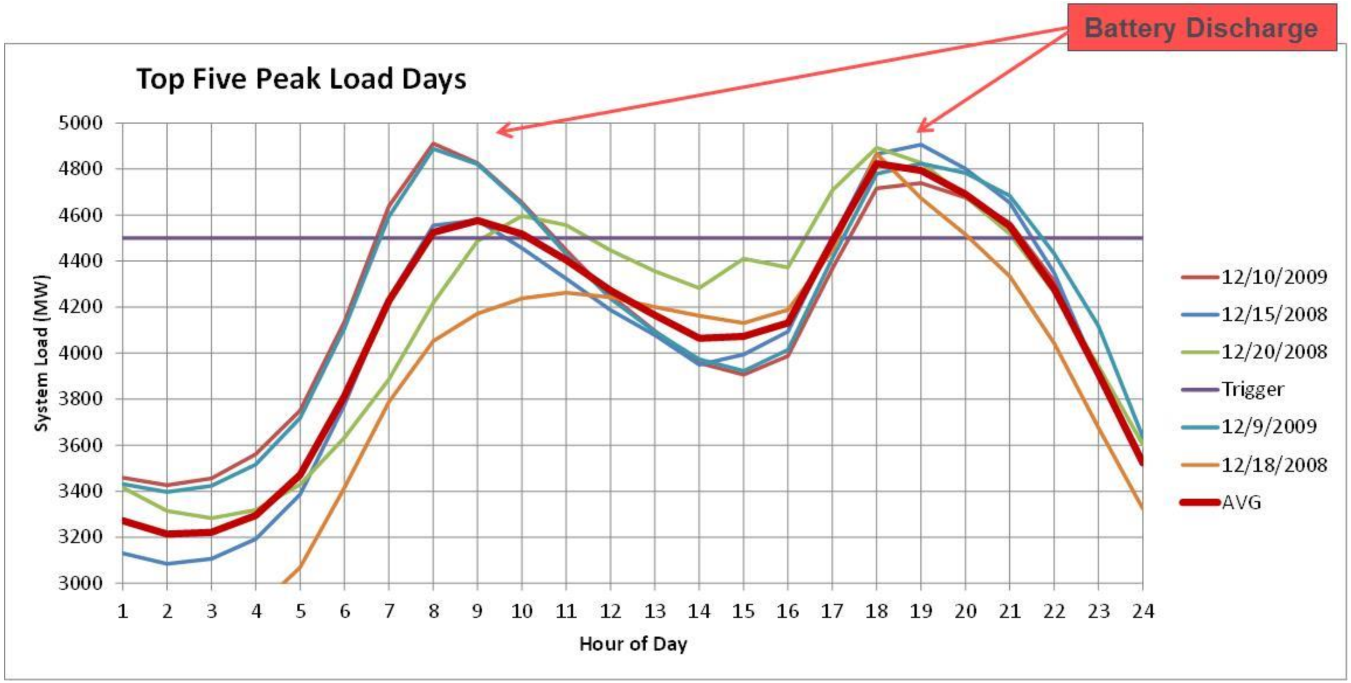
- Hourly wholesale energy market used to determine peak / off-peak price differentials (Mid-C prices from 2011-2016)
- Value obtained by purchasing energy during low price hours and selling energy at high energy price hours – efficiency losses considered





Peak Shaving

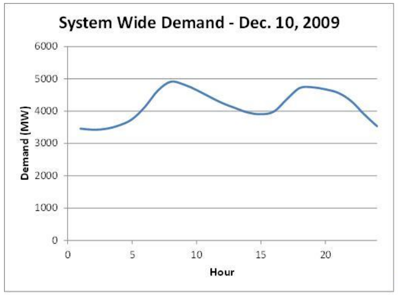
- Capacity value based on the incremental cost of next best alternative investment (peaking combustion turbine) with adjustments for energy and flexibility benefits of the alternative asset, the incremental capacity equivalent of energy storage, and line losses
- Distribution upgrade deferral based on present value benefits of deferring investment in distribution system upgrades

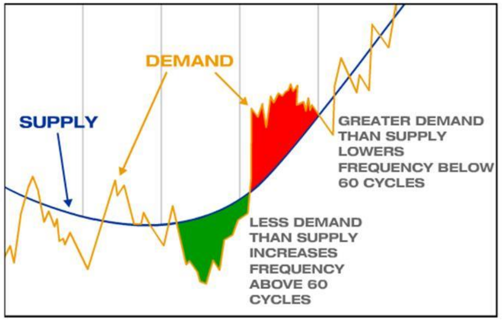


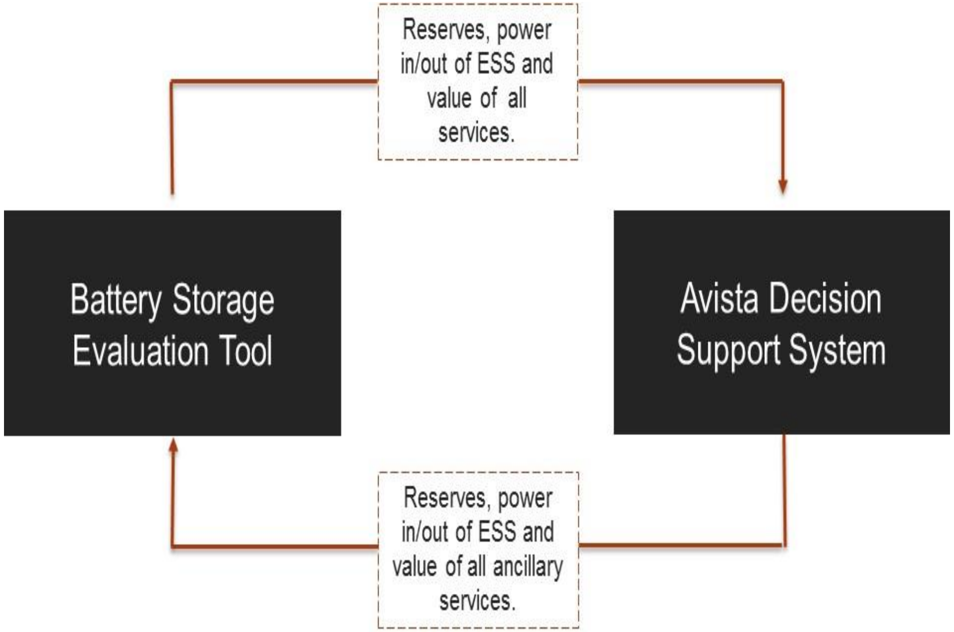
Key Lesson: Values will differ based on presence of markets, local distribution system conditions, and valuation policies.

Ancillary Services

- Battery fills the short-term gaps between supply and demand
- Reduces cost and emissions associated with idling fossil-fuel burning plants
- Use cases include regulation up and down, load following up and down, and spin and non-spin reserves







Primary Frequency Response

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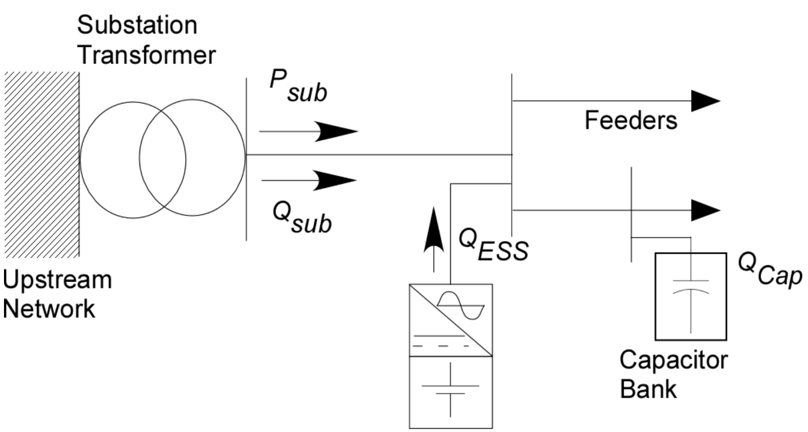
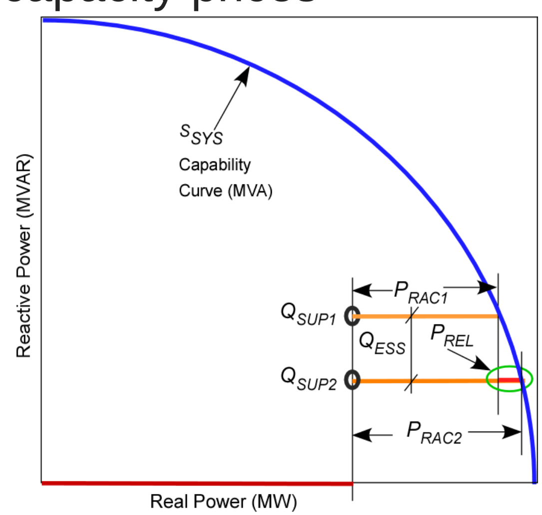
- NERC Standard BAL-003-1 requires that PSE and Avista provide generation capacity as required in response to frequency events
- Based on set points established by utility frequency response screen, PNNL working with each utility defines an appropriate primary frequency response
- No notification; requires 100-second burst of energy
- Value ($44.40/kW-year) estimated based on price paid by CAISO for primary frequency response support to the Bonneville Power Administration

Volt-VAR Support and CVR

- Battery energy storage system (BESS) used to provide reactive power locally, thus reducing energy losses and releasing upstream network capacity
- Benefit limited by available capacity of the BESS inverter to sink/source VAR; handled in post processing after needs of other use cases are met
- CVR factor (% reduction in demand / % reduction in voltage) estimated based on voltage/power data from a series of tests conducted on each battery
- Value of reduced energy consumption based on hourly Mid-Columbia energy index price; value of capacity based on utility capacity prices



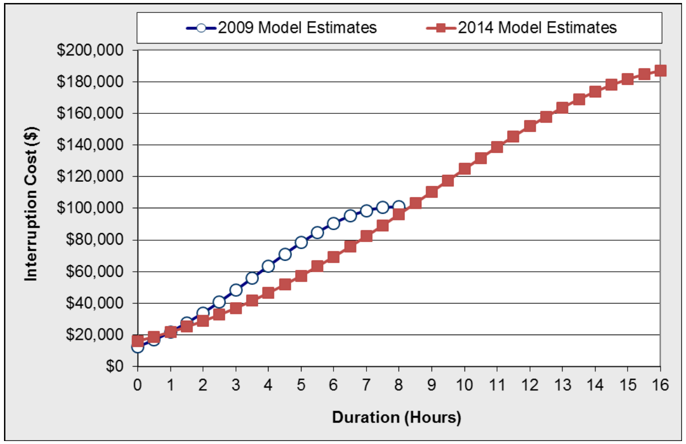
BESS Meeting Local VAR Demand



Release of Upstream Network Capacity

Outage Mitigation

- Outage data
  - Outage data obtained from utility for multiple years
  - Average annual number of outages determined and outages randomly selected and scaled to approximate average year
  - Outage start time and duration
  - Outage cost data varied by customer type
- Customer and load information
  - Number of customers affected each outage obtained from utility
  - Customer outages sorted into customer classes using utility data and assigned values
  - Load determined using 15-minute SCADA information
- Alternative scenarios
  - Perfect foreknowledge – energy storage charges up in advance of inclement weather
  - No foreknowledge – energy on-hand when outage occurs is used to reduce outage impact



Interruption Costs ($2013) by Duration, Medium and Large C&I
Source: Sullivan, M, J. Schellenberg, and M. Blundell, 2015, Updated Value of Service Reliability Estimates for Electric Utility Customers in the U.S. San Francisco, CA.

Key Lesson: Benefits, which can be very large, accrue primarily to the customer and are largely dependent on the effective placement of the ESS. If focused on utility benefits, we would focus on violation costs or lost energy sales.

Bundling Services: How To Do It Optimally

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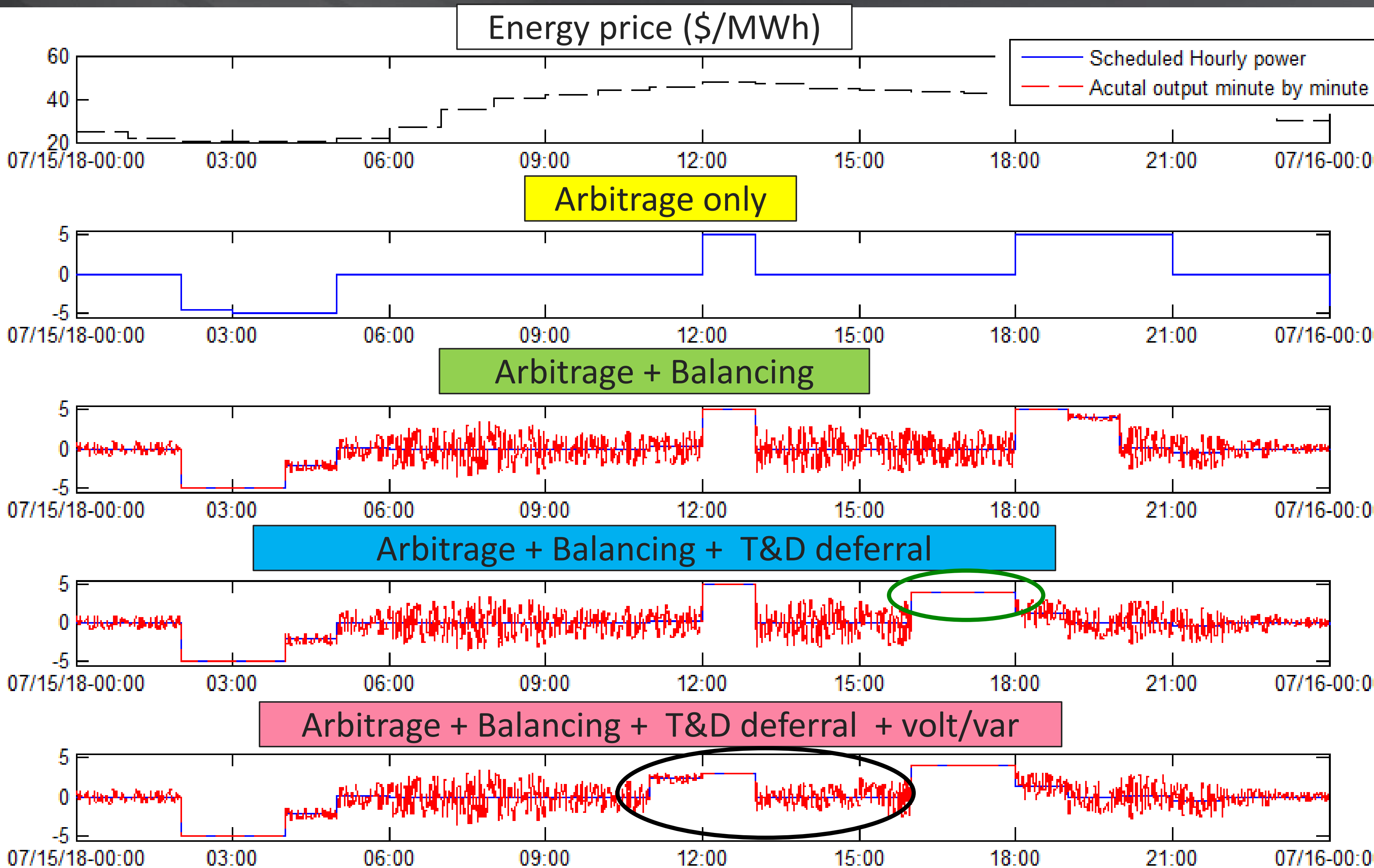

Turner Energy Storage Project

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Issue:

- Power sensitive customer at end of two feeders; ride through capability needed during outages.

Solution:

- Locate 1MW – 3.5 MWh battery near SEL campus

Benefits:

1. Peak capacity
2. Energy arbitrage
3. Ancillary services
4. Volt-VAR control
5. Outage management of critical loads
6. Microgrid operation

UET Battery System in Pullman, WA

Turner Energy Storage Project Value of Voltage Sag Compensation

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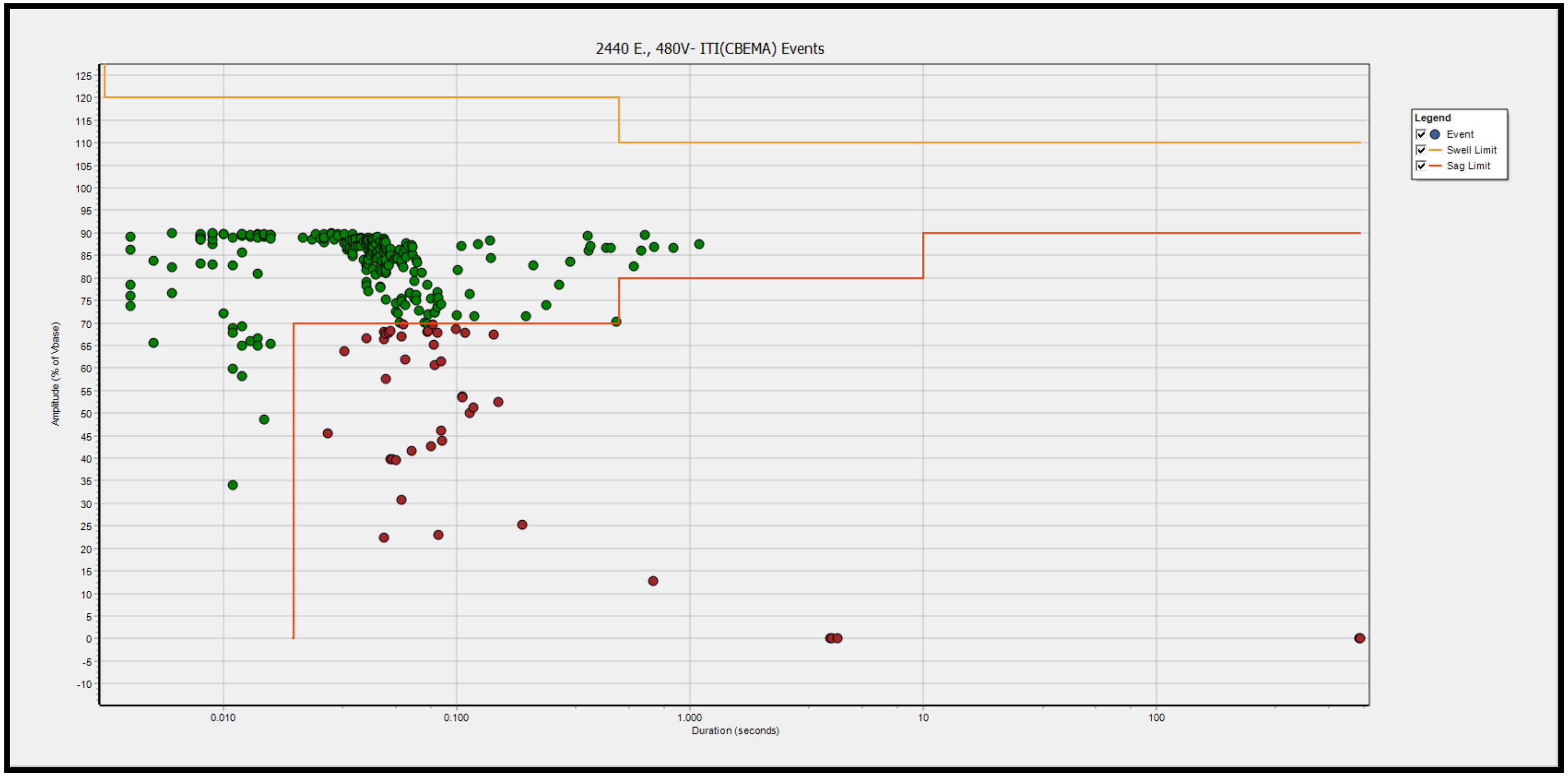

- Sustained voltage sags lead to production disruptions; energy storage could provide voltage sag compensation
- Voltage sags of over 30% for more than 25-100ms could result in machine outages resulting in 2-3 hours of down time; cost of down time estimated at $150,000 per hour
- 30 voltage sags of over 30% for more than 25-100ms, which definitely results in machine outages, occurred over four years for an average annual cost of $2.3-$3.4 million in lost production annually

SnoPUD MESA 1 and MESA 2 Projects

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Issue:

- Broader effort aimed at transforming how utilities manage grid operations through advancement of the Modular Energy Storage Architecture (MESA)

Solution:

- Locate 2MW – 1 MWh li-ion and 2 MW – 8.0 MWh vanadium flow battery systems at two substations in Everett, WA to manage congestion and improve the reliability and operating costs of BPA's transmission grid

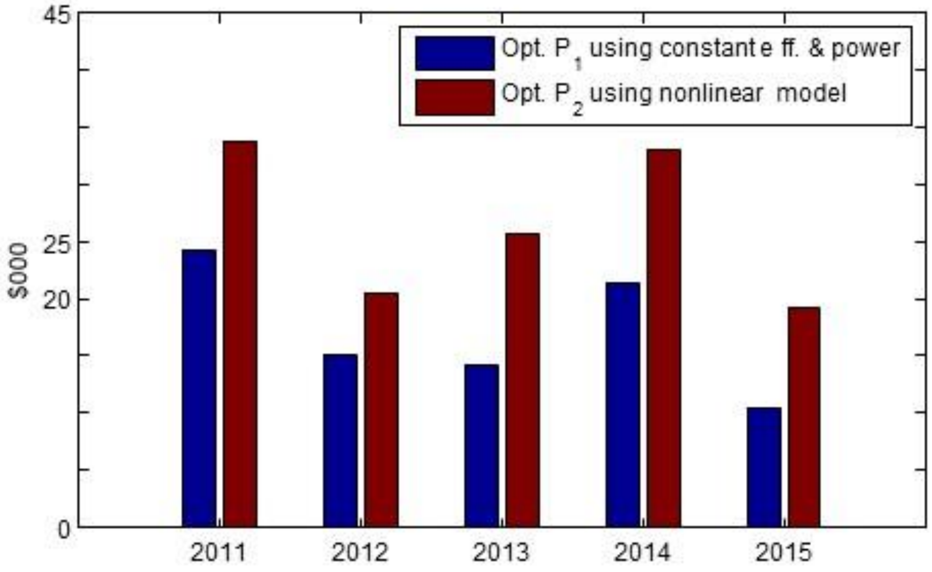
Benefits:

1. Energy arbitrage
2. Minimize load balancing payments to BPA
3. Outage management
4. Demand response
5. Peak winter capacity

MESA 1 - 2 MW / 1 MWh Li-Ion Battery System in Everett, WA.

Non-Linear Battery Model Used to Enhance Arbitrage Value to SnoPUD

Annual 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

Key Lesson: Improving operational knowledge enhances profit potential by finding sweet spots in which to operate the system to provide services with smaller profit margins.

Glacier Project

Issue:

- Frequent transmission-line outages due to vegetation.

Solution:

- Locate 2.0MW – 4.4 MWh lithium-ion battery near Glacier substation to provide (temporary) backup power to distribution circuit.

Benefits:

1. Flexibility services
   1. Energy arbitrage
   2. Regulation up/down
   3. Spin / non-spin
2. Primary frequency response
3. Capacity
4. Outage Mitigation

Glacier Project

- Project costs at $5.3 million without substation upgrades; $7.8 million including substation upgrades. $3.8 million CEF grant factored into estimates above.
- Project benefits
  - Flexibility services at $119/kW-year
  - Capacity at $38.29/kW-year
  - Primary frequency response - $44.40/kW-year
  - Outage mitigation at $172/kW-year
    - Average of four outages per year
    - Average outage lasts 6.4 hours
    - Islanded area in Glacier includes 20 small C&I customers and 38 residential customers
    - All outages successfully mitigated in simulation
    - PSE successfully performed an islanding test recently

Islanded Area in Glacier

CEF II - Decatur Island Substation Energy Storage & Community Solar

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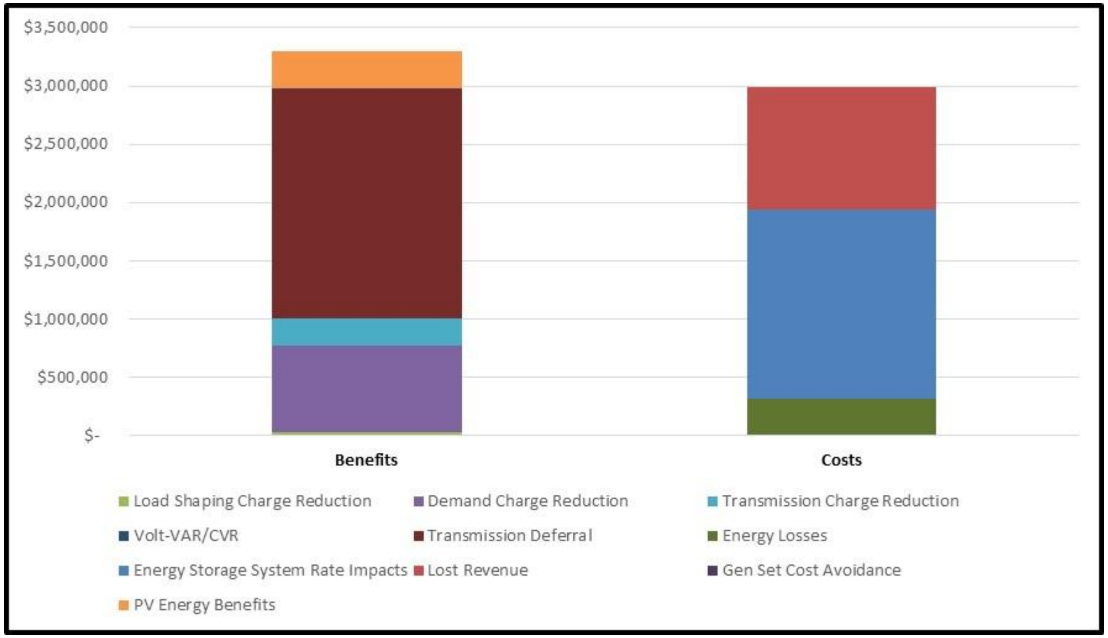
- $1 million grid modernization grant awarded to OPALCO as part of Washington Clean Energy Fund (CEF) II
- 0.5 MW / 2 MWh UniEnergy Technology Vanadium Redox Flow Battery
- 504 kW LG Community Solar Array from Puget Sound Solar
- Demonstrations of value
  - Integration of renewables onto the grid (reduce intermittency of community solar array)
  - Demonstration of islanding, Volt-VAR control, and other advanced control methods
- Potential PV and energy storage benefits:
  - Demand charge reduction
  - Load shaping charge reduction
  - Transmission charge reduction
  - Transmission submarine cable replacement deferral
  - Volt-VAR/CVR
  - Outage mitigation

Results – OPALCO Benefits and Costs (20-Year Present Value Terms)

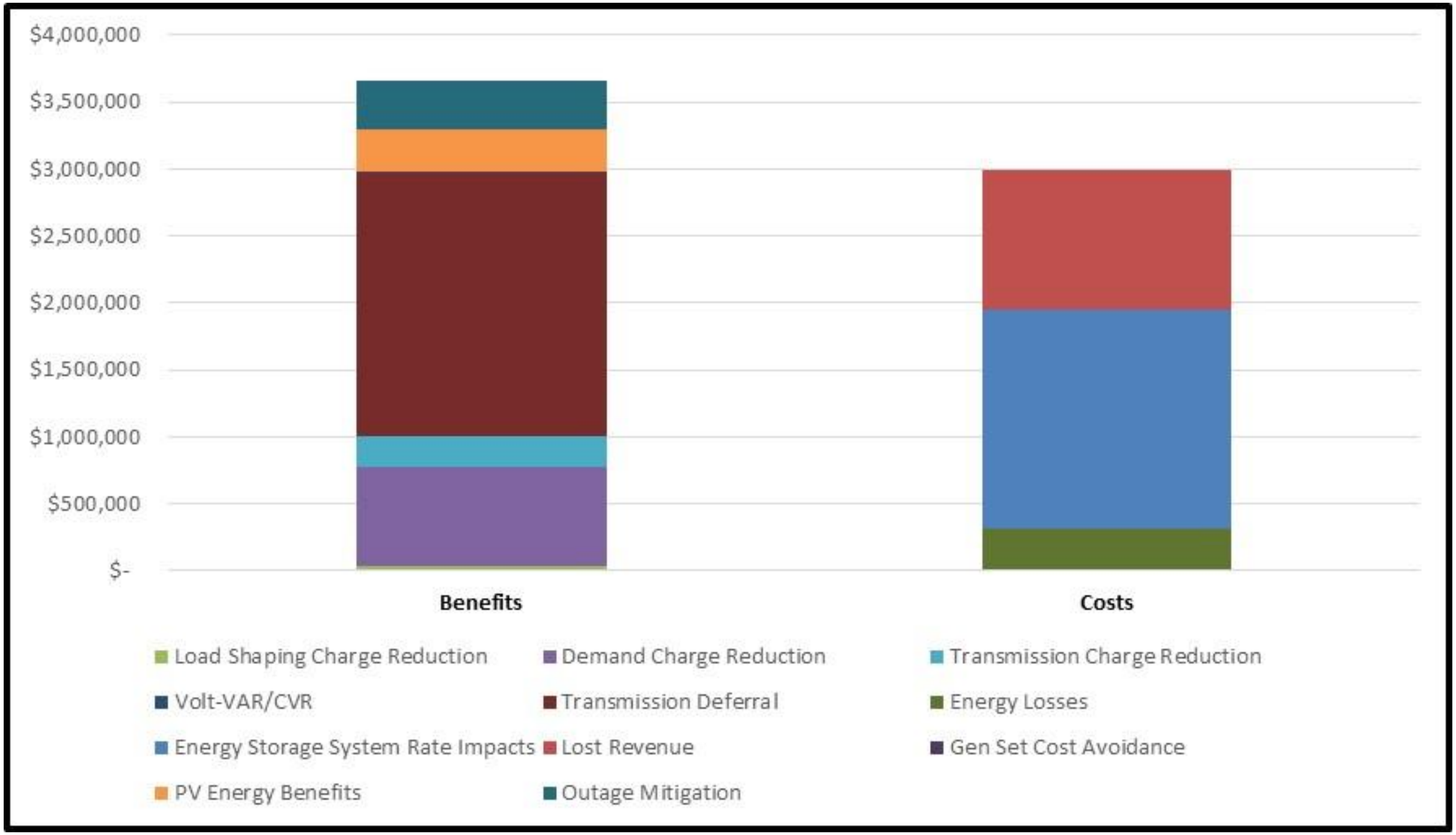
- Total 20-year value of PV and ESS operations at $3.3 million in present value terms, while costs are $3.0 million for a benefit-cost ratio of 1.10
- Benefits largely driven by transmission deferral benefit at $2.0 million in present value terms and ability of storage to reduce transmission and demand charges
- Total system costs
  - Energy storage costs estimated at $1.6 million in present value terms
  - $1.0 million (present value terms) in lost revenue resulting from community solar production
  - $0.3 million in energy costs associated with RTE losses, RTE at 70% for peak shaving



Element	Benefits		Costs	
Load Shaping Charge Reduction	$	36,404		
Demand Charge Reduction	$	739,802		
Transmission Charge Reduction	$	227,331		
PV Energy Benefits	$	313,434		
Volt-VAR/CVR	$	3,380		
Transmission Deferral	$	1,957,878		
Gen Set Cost Avoidance	$	19,706		
Lost Revenue			$	1,048,046
Energy Losses			$	315,457
Energy Storage System Rate Impacts			$	1,630,291
	$	**3,297,936**	**$**	**2,993,795**

Results – OPALCO Benefits and Costs + Outage Mitigation Benefits

- Total 20-year value of outage mitigation benefits are estimated at $356,490 in present value terms; including outage mitigation improves the benefit-cost ratio to 1.22



Battery State of Health Model

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- Goal: Develop a reliable and accurate model to predict battery degradation under various conditions and to integrate as module in economic optimization tool
- Top-down model
  - Quantifying the effects of energy throughput, charge-discharge power, and operating temperature on performance
  - One year of performance data from a grid scale flow ESS was used to extract relevant coefficients to quantify degradation; will be tested against five battery systems (three li-ion and two flow batteries)
  - Approach being further refined by adding depth of discharge, number of cycles, SOC operation range, and time at various voltages.
- Bottom-up model to estimate battery degradation
  - The model includes the effect of cycling and calendar aging, taking into account the effect of temperature and voltage
  - The developed model is being verified against degradation data for a grid-scale Li-ion energy storage system, provided to PNNL by a utility, a leader in grid scale storage implementation
  - The model to date accurately predicted degradation after 18 months of testing.
- Both these approaches will be modified to predict battery degradation across multiple chemistries – various chemistries within Li-ion and flow batteries.

Energy Storage Control Algorithms

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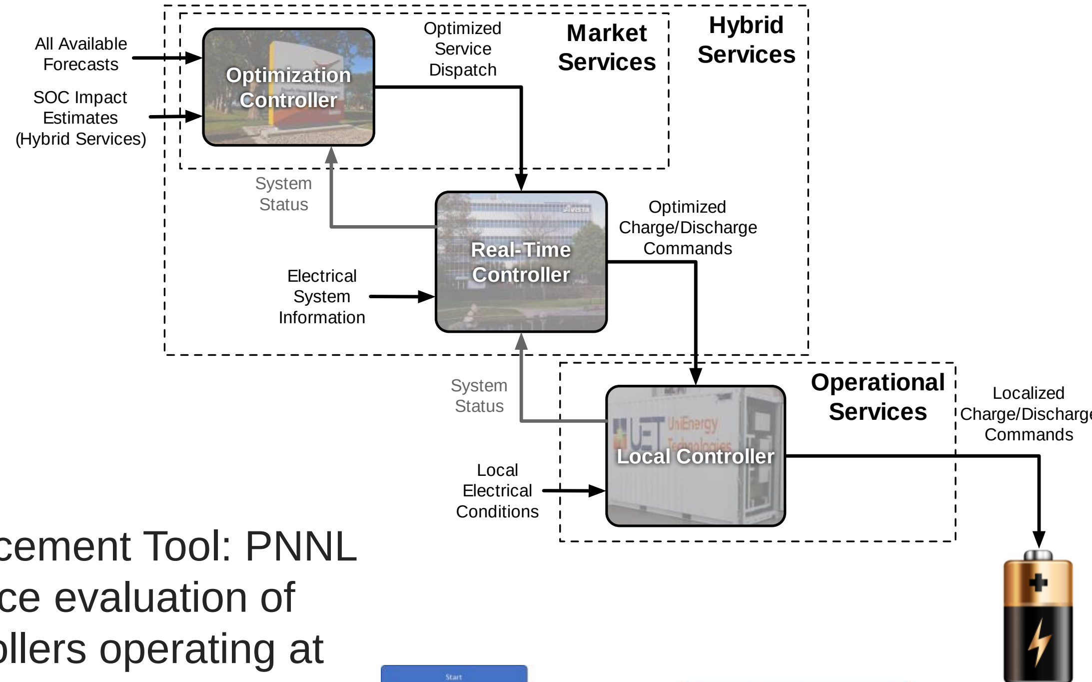
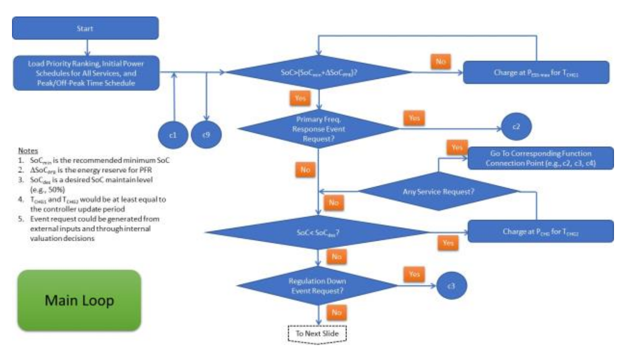
- Development of control strategies
  - Develop outline of control strategies
  - Develop detailed design of control functions and reporting
  - Simulation/implementation of control functions



- Optimization Performance Enhancement Tool: PNNL is developing a tool for performance evaluation of commercial energy storage controllers operating at utility sites. The tool achieves several goals:
  - Enhance learning of the inputs to be considered in developing storage control strategies that could achieve target economic values in real-world situations
  - Enhance performance by finding logic errors in control strategies
  - Evaluate impacts of forecast error on performance of control strategies



The Challenge

- Challenge - Over 3,000 utilities
  - Different grid reliability, resiliency, flexibility, renewable integration challenges
  - Different market structures
  - Different costs of electricity
  - Other competing solution approaches besides energy storage
- What is needed
  - Requires regional and local analysis of deployed storage technologies in diverse markets to develop full understanding of monetized and un-monetized benefits
  - Development of industry standard design tools with fidelity to capture the multi-use value of storage in transmission, distribution, and behind-the-meter (BTM) applications
  - Development of models to characterize and predict storage system performance, and to assess degradation
  - Development of control algorithms and tools to evaluate dispatch controllers
  - New business models

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Background Slides

Value Taxonomy – Establishing a Consistent Set of Services

Category	Service	Definition
Bulk Energy	Capacity or Resource Adequacy	The asset is dispatched during peak demand events to supply energy and shave peak energy demand. The asset reduces the need for new peaking power plants and other peaking resources.
	Energy arbitrage	Trading in the wholesale energy markets by buying energy during off-peak low-price periods and selling it during peak high-price periods.
Ancillary Services	Regulation	An operator responds to an area control error in order to provide a corrective response to all or a segment portion of a control area.
	Load Following	Regulation of the power output of an asset within a prescribed area in response to changes in system frequency, tie line loading, or the relation of these to each other, so as to maintain the scheduled system frequency and/or established interchange with other areas within predetermined limits.
	Spin/Non-spin Reserve	Spinning reserve represents capacity that is online and capable of synchronizing to the grid within 10 minutes. Non-spin reserve is offline generation capable of being brought onto the grid and synchronized to it within 30 minutes.
	Frequency Response	The asset provided energy in order to maintain frequency stability when it deviates outside the set limit, thereby keeping generation and load balanced within the system.
	Flexible Ramping	Ramping capability provided in real-time, financially binding in five-minute intervals in CAISO, to meet the forecasted net load to cover upwards and downwards forecast error uncertainty.
	Voltage Support	Voltage support consists of providing reactive power onto the grid in order to maintain a desired voltage level.
	Black Start Service	Black start service is the ability of a generating unit to start without an outside electrical supply. Black start service is necessary to help ensure the reliable restoration of the grid following a blackout.

Value Taxonomy – Establishing a Consistent Set of Services (cont.)

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Category	Service	Definition
Transmission Services	Transmission Congestion Relief	Use of an asset to store energy when the transmission system is uncongested and provide relief during hours of high congestion.
	Transmission Upgrade Deferral	Use of an asset to reduce loading on a specific portion of the transmission system, thus delaying the need to upgrade the transmission system to accommodate load growth or regulate voltage.
Distribution Services	Distribution Upgrade Deferral	Use of an asset to reduce loading, voltage, or some other parameter on a specific portion of the distribution system, thus delaying or eliminating the need to upgrade the distribution system to accommodate load growth or regulate voltage.
	Volt-VAR Control	Volt-ampere reactive (VAR) is a unit used to measure reactive power in an AC electric power transmission and distribution system. VAR control manages the reactive power, usually attempting to get a power factor near unity.
	Outage management	Use of an asset to reduce the frequency and duration of outages (avoided lost sales, avoided penalties).
	Conservation Voltage Reduction	Use of an asset to reduce energy consumption by reducing feeder voltage.
Customer Energy-Management Services	Power Reliability	Power reliability refers to the use of an asset to reduce or eliminate power outages to customers.
	Time-of-Use Charge Reduction	Reducing customer charges for electric energy when the price is specific to the time (season, day of week, time-of-day) when the energy is purchased.
	Demand Charge Reduction	Use of an asset to reduce the maximum power draw by electric load in order to avoid peak demand charges.
	Demand Response	Demand response provides an opportunity for consumers to reduce or shift their electricity usage during peak periods in response to financial incentives.