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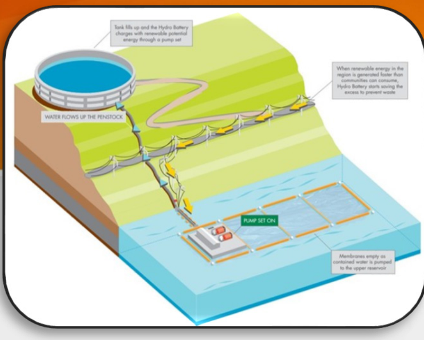

Shell Energy North America's Hydro Battery System

Final Market Assessment Report

June 2018

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U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

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Executive Summary

Pumped storage hydro (PSH) units are highly capable of providing services that are critical for the optimal, reliable, and efficient operation of the electrical grid. PSH is an attractive resource when providing bulk power and ancillary services because of its fast response time, fast synchronization time, and versatility as a generator and a load.

Despite the operational benefits of PSH associated with component durability, high energy storage capacity, and low operations and maintenance costs, projects in the U.S. have stalled due to the presence of high up-front capital costs, an absence of long-term market products, and uncertainty regarding environmental considerations. This report focuses on the economic potential of the small, modular Shell Energy North America (SENA) PSH system called the "hydro battery." The 5 megawatt/30 megawatt-hour SENA Hydro Battery avoids these major barriers because it embodies several important characteristics:

- The small modular design enables scalable development and distributed resourcing;
- Scalability allows developers to adjust PSH design based on topography and markets;
- Distributed PSH resources could enable resiliency options such as microgrids;
- Low cost, modular PSH units will minimize risk exposure to investors; and,
- Pre-fabricated system components, including the in-river floating reservoir, will minimize construction costs, schedules, and safety and environmental impacts by minimizing onsite construction.

Despite the operational benefits inherent in PSH, many of the services it can provide are difficult to quantify due to a lack of available market data. The contribution a PSH unit can provide to the electrical grid is highly dependent on the factors and characteristics of its design as well as its placement on the grid and the combination of other generation technologies being used. Regardless of whether a PSH unit is developed for a regulated utility or in an energy market area, two PSH projects with identical characteristics can have vastly different dispatch operations and portfolios of benefits. Which markets are available for the services provided is also a heavily influential factor on total value. All of these elements require PSH units to have highly site-specific analysis and simulation in order to derive total value and estimate the viability of each project.

The intent of this assessment is to deliver a market value analysis of the small, closed-loop pumped storage units that are configured from a modular pumped storage catalog of standardized functional elements. To select among the potential locations, Pacific Northwest National Laboratory (PNNL) identified the market services offered in several Federal Energy Regulatory Commission power markets, the presence of existing and planned PSH investments, the need to integrate renewables, the presence of transmission and capacity constraints, and other factors that could influence the profitability of PSH. The results of this analysis are presented in Balducci et al. (2017a). Based on the results of the analysis, PNNL consulted with SENA trading and ratified with the U.S. Department of Energy the selection of the Pacific Northwest, the California Independent System Operator (CAISO) region, the New York Independent System Operator (NYISO) region, and Hawaii for analysis. The results of each market assessment are summarized in this report.

The following key lessons and implications can be drawn from the analysis.

1. **The costs presented by SENA for the hydro battery are roughly comparable to those present in the marketplace for electro-chemical battery systems of a similar scale.**

   The all-in capital costs, inclusive of licensing but excluding debt-related costs, are estimated by SENA for the Pearl Hill base project at $743/kWh. While li-ion costs for direct current (DC) modules and battery management systems have fallen to below $400/kWh in some cases, additional power conversion system, construction and commissioning, power control system, and electrical balance of plant costs result in all-in capital costs that are comparable to the hydro battery (Lahiri 2017).

2. **Of the Four Regions Analyzed, the Pacific Northwest and the Hawaiian Island of Oahu Offer the Highest Return on Investment (ROI) Ratios Under the Base Case Configuration.**

   The Pearl Hill reference configuration has a ROI ratio of 1.36 with $39.6 million in present value (PV) benefits compared to $29.0 million in costs. The second highest ROI ratio after the Pacific Northwest region is Hawaii, which offers a benefit cost ratio of 1.16 under the base case and over $41 million in PV benefits. Within the NYISO analysis, only two zones offered a positive ROI under the base case scenario – Hudson Valley (1.08 ROI ratio) and Millwood (1.08 ROI ratio). No other zones within the NYISO region and none of the sub-regions within the CAISO analysis offer an ROI ratio greater than 1.0. ROI ratios for all sub-regions are presented in Table ES.1.

Table ES.1. Base Case Return on Investment Ratios for the Four Regions of Analysis

Region	Sub-Region	Base Case ROI
Pacific Northwest	Pearl Hill	1.36
CAISO Service Territory	PG&E	0.81
	SCE	0.66
	SDG&E	0.87
	Folsom	0.80
	Ramona	0.90
NYISO Service Territory	Capital	0.86
	Central	0.87
	Dunwood	0.91
	Genesee	0.84
	Hudson Valley	1.08
	Long Island	0.86
	Mohawk Valley	0.87
	Millwood	1.08
	North	0.89
	NYC	0.87
Hawaii	Oahu	1.16

3. **The Two Most Valuable Services within the Regions Analyzed are Capacity and Regulation.**

   For the Pacific Northwest analysis, the capacity use case offers $11.4 million in 30-year PV benefits, closely followed by regulation up ($10.6 million). The CAISO analysis shows that within each of the five regions explored, regulation offers the highest benefit at $14.98 million on average. Within NYISO, the Installed Capacity Market provides the highest benefit for each sub-region at an average of $15.4 million, followed by regulation ($9.8 million). Capacity provides the highest benefit within the Hawaii hydro battery analysis as well at $25.3 million in PV benefits. Figure ES.1 presents stacked benefits estimated for the hydro battery within each region compared to system costs adjusted for regional price differences.

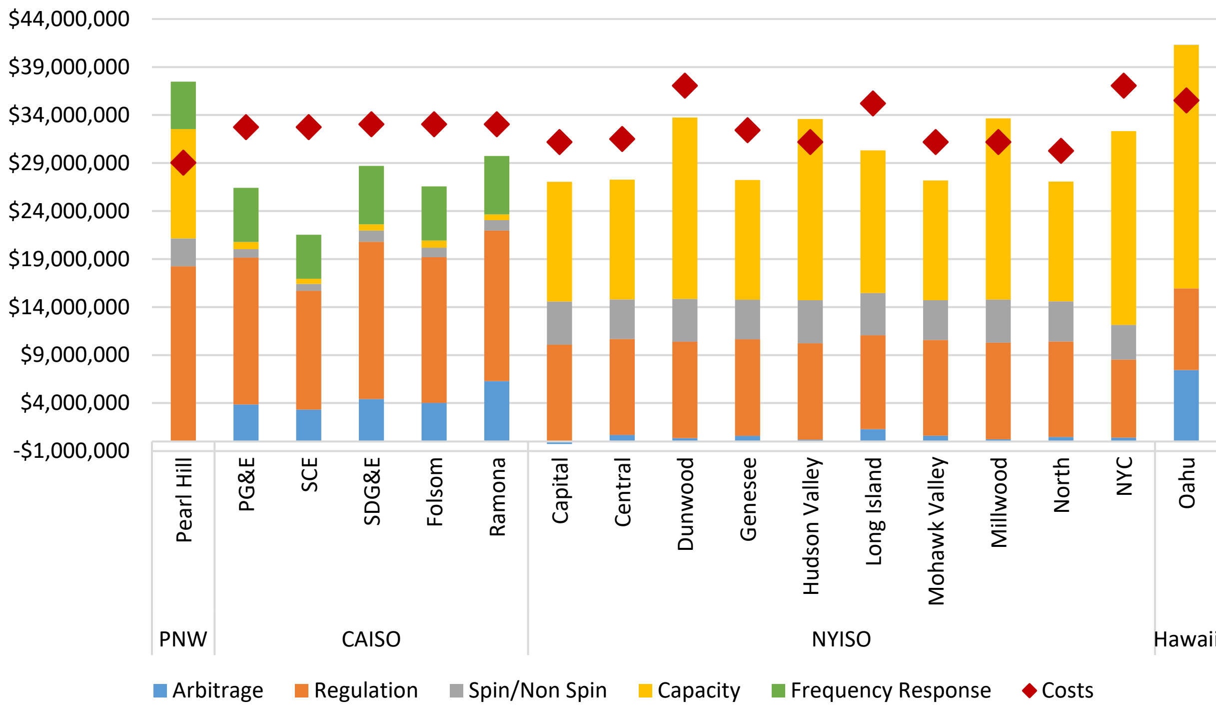

Figure ES.1. Base Case Benefits versus Costs for All Regions by Use Case

4. **Frequency Response Provides High Value as a Use Case Despite Only Requiring a Small Number of Application Hours in a Given Year.**

   For the Pacific Northwest, frequency response provides $4.9 million in PV benefits despite only being required for 17 hours on an annual basis. Within CAISO, frequency response accounts for only 5 percent of all annual hydro battery hours but provides $5.6 million in 30-year PV benefits. Hawaii, however, obtains much lower value comparatively with just under $21 thousand from fast frequency response benefits over the life of the project.

5. **Sensitivity Analysis Shows Positive Returns on Investment in both Low Cost and Mature Cost Methods across Each Region.**

   The low-end cost scenario covers the lower end of the ranges of uncertainty around plant and membrane capital costs (minus 30 percent and 50 percent, respectively). Under this scenario, all locations within all regions show a positive ROI ratio except for the Southern California Edison (SCE) region within the CAISO analysis, which returns an ROI ratio of 0.90 (Figure ES.2). The mature system cost scenario, which incorporates learning from licensing and building the first SENA Hydro Battery, includes 30 percent lower capital costs and only $1 million for licensing costs. This scenario shows identical results as the low-cost scenario with all locations returning a positive ROI ratio except SCE, which produces a ratio of 0.88.

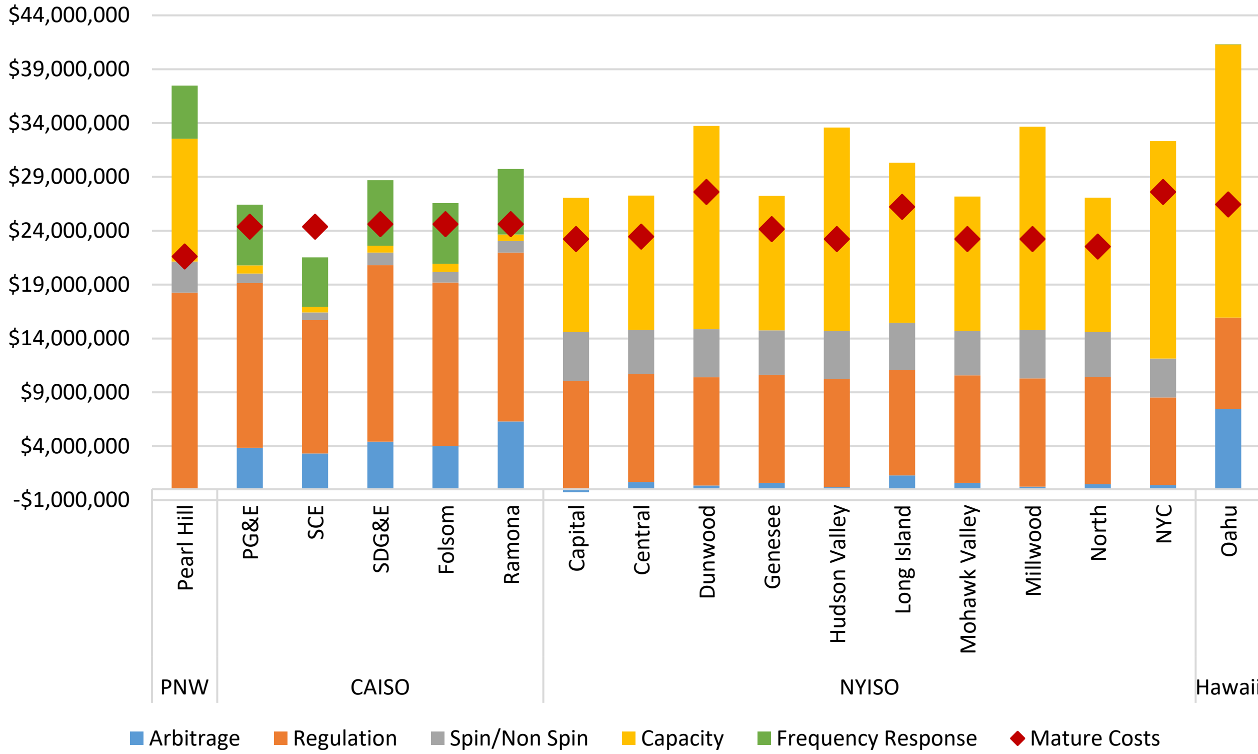

Figure ES.2. Base Case Benefits versus Mature Costs for All Regions by Use Case

Acknowledgments

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Acronyms and Abbreviations

ACE	area control error
ADR	automated demand response
AF	acre-foot
AGC	automatic generation control
B&V	Black & Veatch
BPA	Bonneville Power Administration
BSET	Battery Storage Evaluation Tool
CAISO	California Independent System Operator
CEC	California Energy Commission
CFS	cubic feet per second
CPUC	California Public Utility Commission
DC	direct current
DOE	U.S. Department of Energy
EIM	Energy Imbalance Market
ESS	energy storage system
FERC	Federal Energy Regulatory Commission
FFR	fast frequency response
HDPE	high-density polyethylene
HECO	Hawaiian Electric Companies
HP	Horsepower
Hz	hertz
ICAP	Installed Capacity
IOU	investor owned utility
LAP	load aggregation point
LMP	locational marginal price
LRA	local regulatory authority
LSE	load serving entities
Mid-C	Mid-Columbia wholesale energy market
MW	megawatt(s)
MWh	megawatt hour(s)
NERC	North American Electric Reliability Corporation
NWPP	Northwest Power Pool
NYC	New York City
NYISO	New York Independent System Operator
PG&E	Pacific Gas & Electric
PGE	Portland General Electric

PLC	programmable logic controller
PNNL	Pacific Northwest National Laboratory
PSE	Puget Sound Energy
PSH	Pumped storage hydro
PV	present value
RA	Resource Adequacy
ROI	Return on Investment
RPM	revolutions per minute
RTE	round trip efficiency
SA	sensitivity analysis
SCE	Southern California Edison
SCL	Seattle City Light
SDG&E	San Diego Gas & Electric
SENA	Shell Energy North America
SMM	system mileage multiplier
SOC	state-of-charge
SSPC	Salem Smart Power Center
UV	ultraviolet
WECC	Western Electricity Coordinating Council

Contents

Figures

Tables

1.0 Introduction

Pumped storage hydro (PSH) units are highly capable of providing services that are critical for the optimal, reliable and economically efficient operation of the power system. Some of these services, however, can often be difficult to quantify due to a lack of available market data. PSH is an attractive resource when providing bulk power and ancillary services because of its fast response time, fast synchronization time, and versatility as a generator and a load.

The contribution of value and service a PSH unit can provide to the power system is highly dependent on the factors and characteristics of its design as well as its placement on the grid and the combination of other generation technologies being used. Regardless of whether a PSH unit is constructed in a regulated utility or in a restructured market, two PSH projects with identical characteristics can have vastly different dispatch operations and portfolios of benefits (Koritarov et al. 2014). Which markets are available for the services provided is also a heavily influential factor on total value that can be derived. All of these elements require PSH units to have highly site-specific analysis and simulation in order to derive total value and estimate the viability of a project.

1.1 Project Synopsis

The Pacific Northwest National Laboratory (PNNL) scope of work focuses on the economic potential of the small, modular Shell Energy North America (SENA) PSH unit. Despite the operational benefits of PSH associated with component durability, high round-trip efficiency (RTE) rates and low operations and maintenance (O&M) costs, projects in the U.S. have stalled due to the presence of high up-front capital costs, an absence of long-term market products deterring high capital investment, and uncertainty regarding environmental considerations. The proposed PSH technology would avoid these major barriers because it embodies several important characteristics:

- The small modular design enables scalable development and distributed resourcing;
- Scalability allows developers to adjust PSH design based on topography and markets;
- Distributing smaller PSH resources could enable resiliency options such as microgrids;
- Low-cost, modular PSH units will minimize risk exposure to investors; and,
- Pre-fabricated system components, including the in-river floating reservoir, will minimize construction costs, schedules, and safety and environmental impacts by minimizing onsite construction.

PNNL has worked closely with SENA staff to evaluate the economic potential of the SENA small, modular PSH concept referred to throughout this document as a “hydro battery”. Tasks performed by PNNL in this project are shown in a task flow diagram in Figure 1.1. The first task was addressed through our previous report that defined the regions for market analyses. Under Task 2, PNNL refined the methods used in the market valuation assessment, modified the battery storage evaluation tool (BSET) as required to perform the analysis, and obtained all required data. Task 3 involved the evaluation of the economic benefits of optimally bundled services, with an output of a technical report. This is that technical report. In Task 4, PNNL will update results based on cost and performance data collected by other team members throughout the study. Task 4 will be completed in 2019.

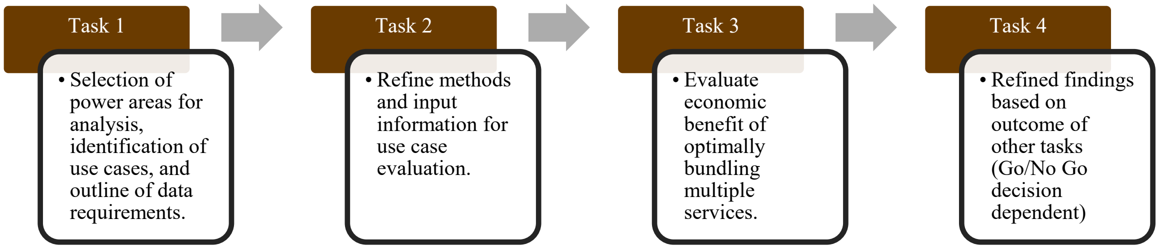


Figure 1.1. Task Flow Diagram

1.2 The Shell Energy North America Hydro Battery

The proposed SENA Hydro Battery is a small modular PSH concept that can be configured as closed-loop or open-loop using tanks and floating reservoirs. Power capacity is similarly scalable with independent pump and generator sets. The reference configuration (Hydro Battery Pearl Hill) would be capable of generating up to 5 megawatts (MW) of power while pumping at up to 9 MW. The additional pumping ability results in a total regulation up/down capacity of 14 MW, equivalent to a 7 MW battery system. The hydro battery has the capacity to store up to 30 megawatt-hours (MWh) of energy (SENA 2017).

Figure 1.2 presents a high-level rendering of a closed-loop configured SENA Hydro Battery example. The upper reservoir consists of a lined corrugated steel tank with a 26.5 acre-foot (AF) operating volume. The proposed tank is approximately 300 feet in diameter (~1.6 acres) and around 20 feet tall. It has approximately two inches of insulation around the perimeter. The tank also has an insulated floating roof for the purpose of water temperature protection, and wildlife and debris exclusion. The tank would feature multiple ports for instruments, as well as a bottom penetration for the penstock inlet, likely featuring baffles to prevent vortex formation (SENA 2017). The lower reservoir consists of a flexible sealed membrane floating in an existing body of water. The proposed construction of the lower reservoir could be divided into smaller, more manageable cells, secured to high-density polyethylene (HDPE) pipe floats, with smaller diameter pipe floats between the cells to allow water to transfer freely between the cells. The membrane material will likely be made of a polyuria, which is an elastomer used in pond liners and secondary containment applications. The material requires no HDPE-style welding, suffers no memory effects, is impermeable and is ultraviolet (UV) stable. The lower reservoir cells are moored to the power platform and shore anchors via steel cables.

The penstock is comprised of a single 36-inch carbon steel pipe, which will be used for delivering water between the upper and lower reservoirs. The 36-inch penstock would be approximately 5,800 feet long. The proposed intake uses five vertical turbine pumps arrange in parallel.

The power platform is either a moored floating platform interconnected with high pressure ball valve or a fixed structural steel platform supported at water's edge by piles and rock anchors that would cantilever pump intakes over the floating reservoir. Five 2,400 horsepower (HP) vertical turbine pumps are arranged in parallel. The pump proposed for use is the VIT 18DXC/20CHC from ITT Goulds. It is a 7-stage vertical turbine pump, running at 1,780 revolutions per minute (rpm), generating 1,375 feet of head at the rated flow of 12.6 cubic feet per second (cfs) per pump. The runout flowrate of each pump is 13.6 cfs.

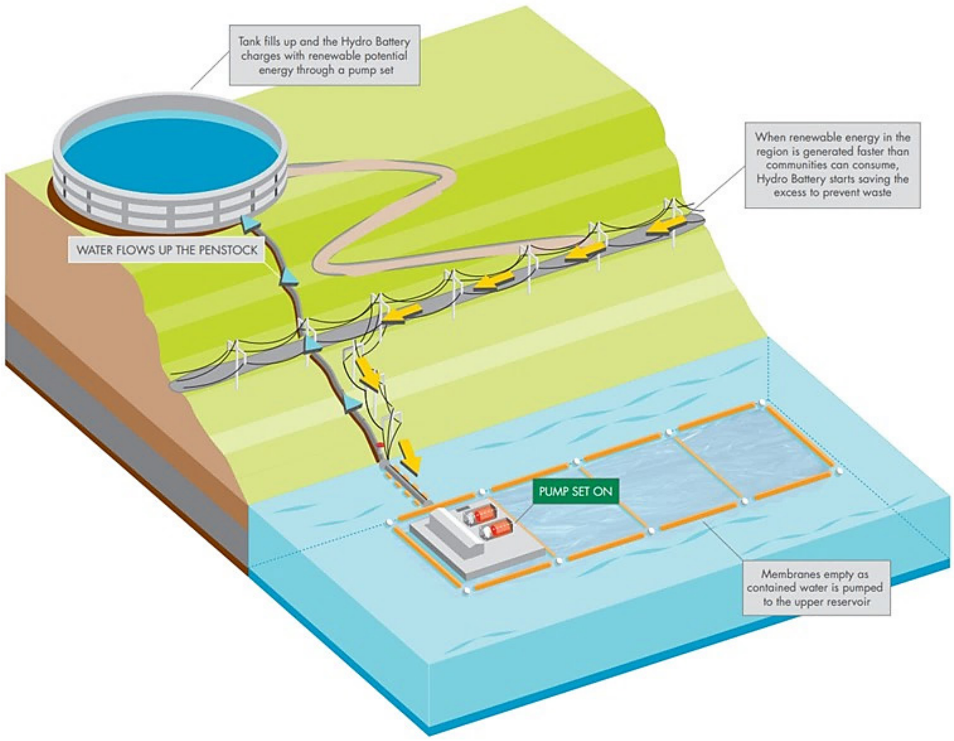


Figure 1.2. SENA Hydro Battery Rendering

There SENA Hydro Battery has four operating modes:

1. **Pumping Mode**. Water is pumped from the lower reservoir to the upper reservoir using five water pumps located at the lower reservoir. Each pump has its own discharge valve and recycle control valve. During tank filling, a platform isolation valve and tank isolation valve are open. Water continues to fill the tank until either a stop command is issued, or a high-water level is reached. When pumping, a fish screen motor slowly moves to keep the screen free from debris. Initial filling of the penstock will be done locally by operating the pumps using the local hand-off-auto switches and manipulating the pump discharge and recycle valves manually.
2. **Generating Mode**. In the generating mode, water flows from the penstock and/or from the pumps if they are running to spin the turbine generator. The turbine control system keeps the generated power in sync with the local electrical system and power is exported onto the 25kV grid through the power module. The amount of power output by the generator is controlled by a manual set point sent from programmable logic controller (PLC)-A to the generator PLC located in the generator module.
3. **Spinning Reserve Mode**. In spinning reserve mode, the turbine inlet valve remains open, but the water jet nozzles remain closed. The turbine runner spins freely while the generator is synchronized to the grid and rotates using power from the utility system to overcome friction and resistance.
4. **Standby Mode**. When not operating in either generating or spinning reserve mode, pump discharge valves and turbine inlet valves are closed while manual penstock isolation valves remain open.

The generation and pumping efficiencies of the SENA Hydro Battery are estimated at 84.49 percent and 79.55 percent, respectively. The RTE for the unit is, therefore, estimated at 67.21 percent (Steenkamp 2017).

1.3 Definition of Regions and Use Cases

The intent of this assessment is to deliver a market value analysis of the small closed-loop pumped storage units that are configured from a modular pumped storage catalog of standardized functional elements. To select among the potential locations, PNNL identified the market services offered in several Federal Energy Regulatory Commission (FERC) power markets, the presence of existing and planned PSH investments, the need to integrate renewables, the presence of transmission and capacity constraints, and other factors that could influence the profitability of PSH. The results of this analysis are presented in Balducci et al. (2017a). Based on the results of the analysis, PNNL consulted with SENA trading and ratified with the U.S. Department of Energy (DOE) the selection of the Pacific Northwest, the California Independent System Operator (CAISO) region, the New York Independent System Operator (NYISO) region, and Hawaii for analysis (Figure 1.3). The results of each market assessment are summarized in this report.

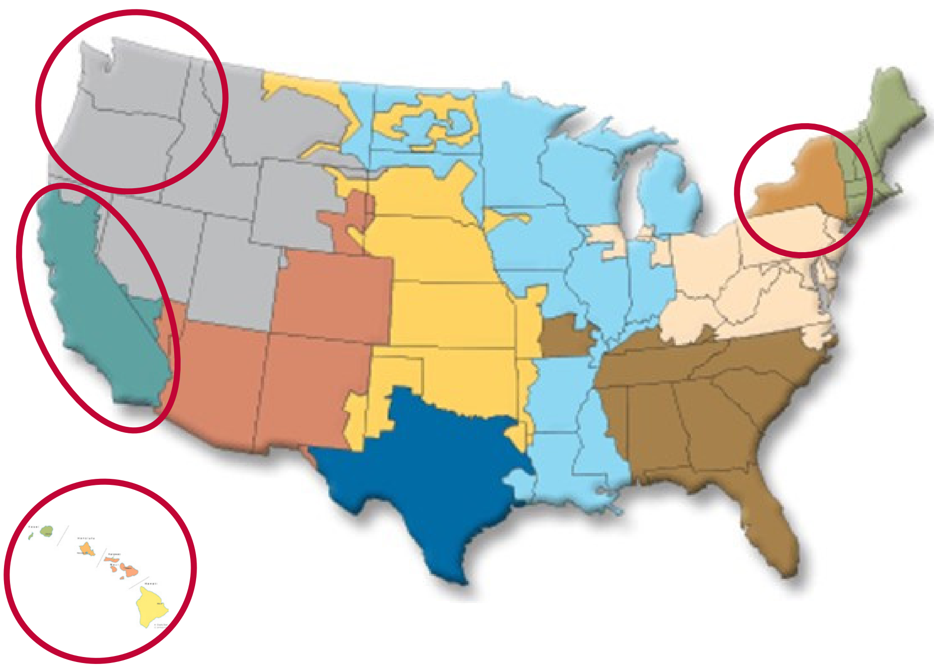


Figure 1.3. Regions Defined for Market Assessments

PNNL previously defined the PSH operational scenarios to be evaluated in this project – use cases that reflect a wide range of potential market prices, product tariffs, and market demand possibilities, as well as alternative combinations of products based on likely future pricing (Balducci et al. 2017a). Those use cases were later modified based on the outcome of additional research and data collection activities. The evaluation of these services reflects the operational characteristics of the SENA Hydro Battery and the avoided cost and/or market benefits measured in the four areas selected for further analysis.

The value of these use cases depends on the operational characteristics of the PSH system and policy and market data collected from market sources and other similar assessments PNNL has conducted for energy storage systems located in the Northwest Power Pool, CAISO, and Independent System Operator New England markets. Based on our assessment of the four areas under evaluation, the use cases identified in Table 1.1 were considered in each assessment.

Table 1.1. Energy Storage Services Selected for Evaluation

#	PSH Services	CAISO	Hawaii	NYISO	Pacific Northwest
1	Energy shifting (arbitrage)*	X	X	X	X
2	System capacity	X	X	X	X
3	Regulation Services	X	X	X	X
4	Spin Reserve	X		X	X
5	Non-Spin Reserve	X		X	X
6	Frequency Response	X	X		X

*In the Pacific Northwest, several utilities participate in both the Mid-Columbia (Mid-C) and Western Energy Imbalance markets.

2.0 Energy Storage Valuation Methodology and Cost Estimates

2.1 Use Cases

PNNL has evaluated the economic benefit of a hypothetical SENA hydro battery configuration located in the four regions described previously. The following use cases were defined, modeled, and monetized within the analysis:

1. **Arbitrage** - Trading in the wholesale energy markets by buying energy during off-peak, low-price periods and selling it during peak, high-price periods.
2. **Capacity or Resource Adequacy** - The energy storage system (ESS) is dispatched during peak demand events to supply energy and shave peak energy demand. The ESS reduces the need for new peaking power plants and other peaking resources.
3. **Regulation Up and Down Services** - An ESS operator responds to an area control error (ACE) in order to provide a corrective response to all or a segment portion of a control area.
4. **Frequency Response** - The ESS provides energy in order to maintain frequency stability when it deviates outside the set limit, thereby keeping generation and load balanced within the system.
5. **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.

It is important to note that methods used to evaluate each of the above use cases can vary by location and individual factors must be accounted for to ensure the complete and accurate analysis of benefits. Overall, the level of benefits received through the implementation of the above use cases is highly dependent on the presence of markets, energy costs, as well as the mix of generation assets. For this reason, the researchers took careful consideration when evaluating benefit streams within each of the included hydro battery regions.

The remainder of this section defines the approaches used in assessing the benefits of each use case specific to each evaluated location. Appendix A presents a use case taxonomy and defines several other use cases that are broadly applicable to energy storage systems.

2.1.1 Energy Arbitrage

2.1.1.1 Arbitrage Overview

Arbitrage is the practice of taking advantage of differences between two market prices. In the context of electric energy markets, PSH can be used to charge during low-price periods (i.e., buying electricity) in order to discharge the stored energy during periods of higher prices (i.e., selling during high-priced periods). The economic reward is the price differential between buying and selling electrical energy, minus the cost of RTE losses during the full charging/discharging cycle. The SENA Hydro Battery could provide up to 30 MWh of energy.

2.1.1.2 Pacific Northwest

For the Pacific Northwest analysis, energy price data was obtained from Powerdex for the 2011–2016 time period. The hourly price data provided by Powerdex formed a portion of the basis of the calculations. Figure 2.1 presents hourly, 2015 price data for illustrative purposes. Prices range from a high of over $220/MWh to a low of $-3.14/MWh.

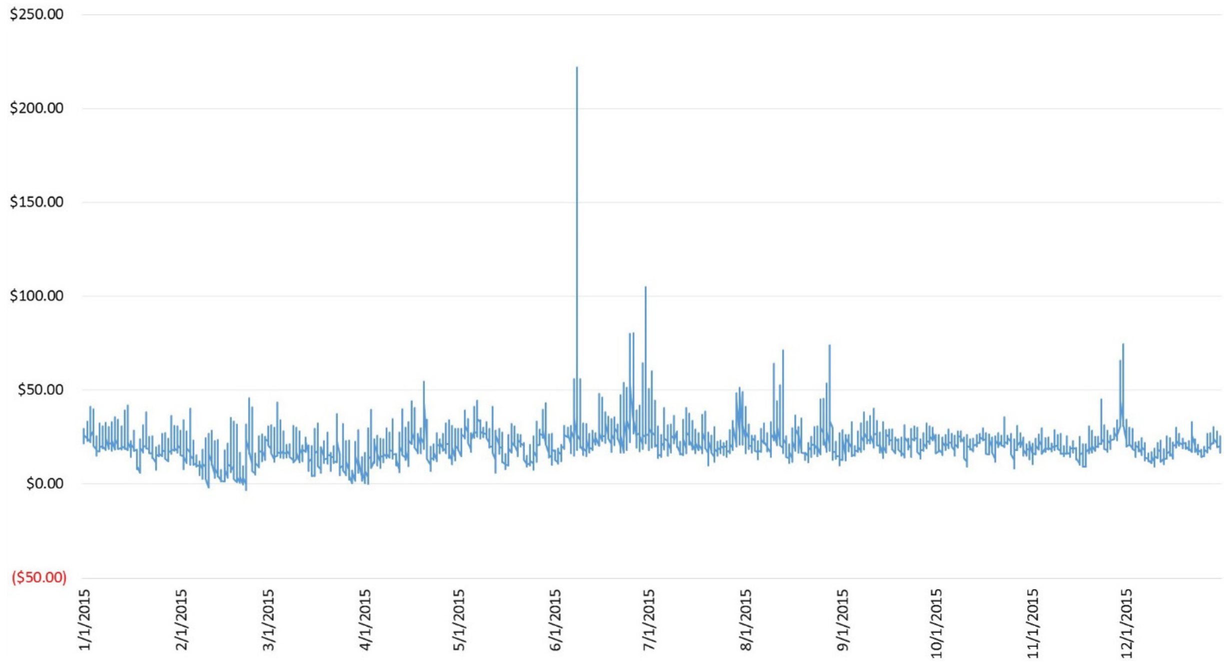


Figure 2.1. 24-hour Energy Storage Schedule

2.1.1.3 CAISO

Energy price data was obtained for three load aggregation points (LAPs) in CAISO for the 2015–2017 time period. Figure 2.2 presents a map of the LAPs, which correspond roughly with the Pacific Gas and Electric (PG&E), San Diego Gas and Electric (SDG&E), and Southern California Edison (SCE) service territories. In addition, two site-specific locational marginal price (LMP) points were also obtained for this study. The sites included in the analysis are Folsom (located within in the PG&E LAP in Sacramento County, California) and Ramona (located within SDG&E's LAP in San Diego County). These two sites were selected as a means to evaluate differences between LAP and LMP values and are both in areas where PSH could feasibly be sited.

Figure 2.2. CAISO LAPs Corresponding to the Three IOUs – PG&E, SCE, and SDG&E

The hourly price data obtained for the PG&E LAP formed a portion of the basis of the calculations. Figure 2.3 presents hourly 2015 PG&E LAP price data for illustrative purposes. Prices range from a high of over $150/MWh to a low of $15/MWh.

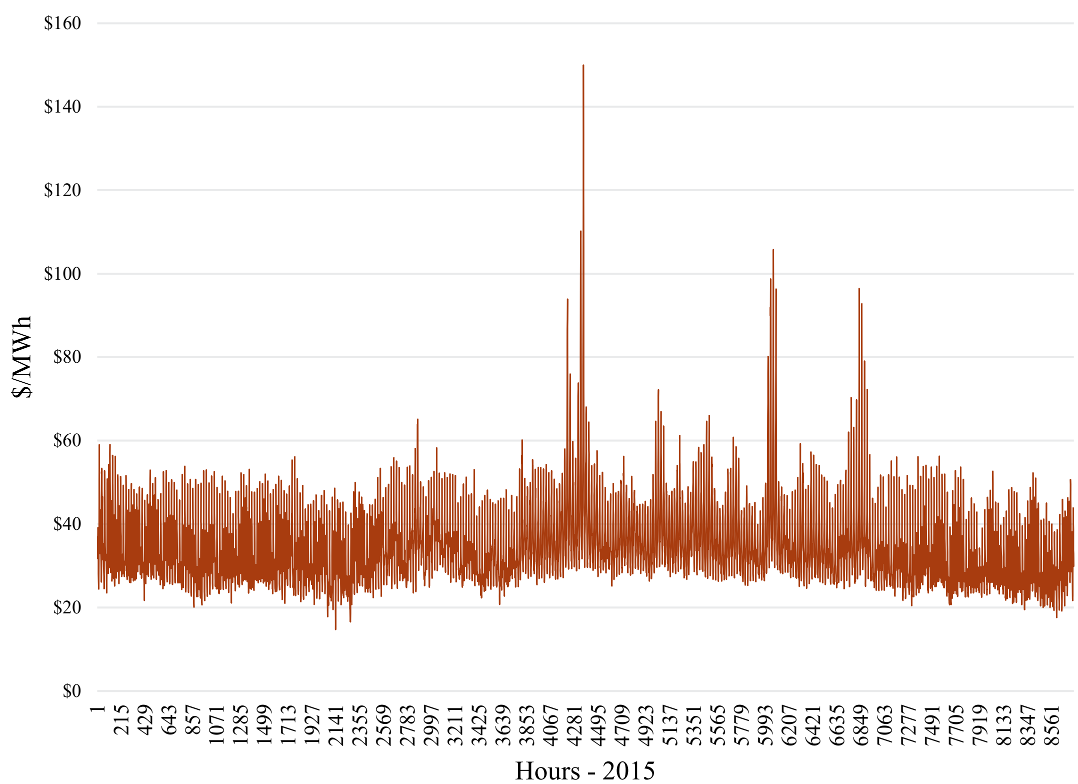


Figure 2.3. Hourly Prices at the PG&E LAP, 2015

2.1.1.4 NYISO

To obtain values for arbitrage in the NYISO, energy price data was obtained for 10 NYISO electric regions/zones: Capital, Central, Dunwood, Genesee, Hudson Valley, Long Island, Mohawk Valley, Millwood, North, and New York City (NYC) (Figure 2.4). Data cover the 2015–2017 time period. Arbitrage values were calculated for each of the 10 zones.

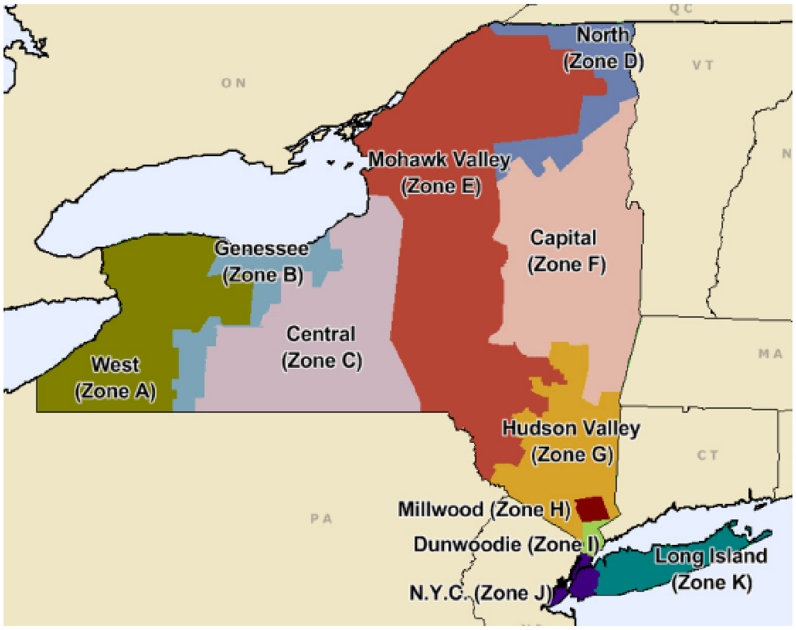


Figure 2.4. NYISO Zones

2.1.1.5 Hawaii

The focus of the Hawaiian market assessment is the island of Oahu. There are no energy markets on Oahu as all the energy is delivered by the Hawaiian Electric Companies (HECO). As such, the values used for arbitrage were developed by Black and Veatch (B&V) under contract to HECO and represent the hourly marginal production cost of energy that could be avoided if energy could be provided to the system at no cost.

The average estimated hourly energy cost in 2018 is high relative to other markets across the U.S. at \$121/MWh, while the minimum cost is \$85/MWh and the highest cost was \$159/MWh. By 2025, the average value is forecast to grow to \$157/MWh, representing an average annual rate of growth of 3.9 percent over that period (Black and Veatch 2017).

2.1.2 Capacity or Resource Adequacy

2.1.2.1 Capacity/Resource Adequacy Overview

When providing capacity or resource adequacy, PSH is dispatched during peak demand events to supply energy and shave peak energy demand. The PSH reduces the need for new peaking power plants and other peaking resources. Resource adequacy (RA) requirements are in place to ensure that energy providers have sufficient assets and capacity to meet their peak demand and can be required on both a local and regional level.

2.1.2.2 Pacific Northwest

To estimate the days and times during which capacity resources would be called upon in the Pacific Northwest study, the researchers acquired demand response data for Portland General Electric (PGE), a utility located in Portland, Oregon. Between 2013 and 2016, there were 27 automated demand response (ADR) events. ADR events for 2016 are presented in Table 2.1. These were used as the basis of the capacity requirements assigned to the hydro battery. The total event statistics were scaled down to a 5 MW capacity contract.

Table 2.1. 2016 ADR Events

Date	Beginning Time	Duration (Hours)	PSH MW Achieved	PSH MWh Achieved
1/6/2016	5:00 PM	2	5.0	10.0
2/17/2016	5:00 PM	1	5.0	5.0
2/24/2016	4:00 PM	1	5.0	5.0
7/28/2016	4:00 PM	3	5.0	15.0
8/12/2016	4:00 PM	3	5.0	15.0
8/18/2016	4:00 PM	3	5.0	15.0
12/8/2016	5:00 PM	3	5.0	15.0
12/14/2016	5:00 PM	3	5.0	15.0

The capacity value was monetized based on the cost of capacity minus energy and flexibility benefits estimated by PGE ($120/kW-year), with a constraint set around the hours/days during which the PSH must reserve capacity to provide capacity services (Navigant 2017).

2.1.2.3 CAISO

The CAISO RA program is designed to ensure that Load Serving Entities (LSEs) have sufficient capacity either on hand or contracted to satisfy both their peak load as well as a 15 percent reserve margin each month. Their individual reserve requirements are determined by demand forecasts of system-coincident peak load that are reviewed by the California Energy Commission (CEC). When providing capacity or resource adequacy, PSH can be dispatched to supply energy or ancillary services – regulation, spinning reserve, and non-spinning reserve. The PSH facility qualifying as RA capacity reduces the need for new generating capacity, either for energy or ancillary services.

There are three types of reserves that must make up their total RA requirement:

1. *System Resource Adequacy* – Any capacity that contributes to the overall RA requirement of an LSE.
2. *Local Resource Adequacy* – Capacity located within a local area where load > transmission capacity. This can be set by the Local Regulatory Authority (LRA).
3. *Flexible Resource Adequacy* – Capacity that is capable of ramping in under three hours. Amount needed varies monthly and is determined by an annual study by the ISO.

Resources may "double count" in some cases. That is, local resources that are also flexible may count towards all three requirements. This is demonstrated in Figure 2.5 provided by ICF International, Inc. (Milligan and Madan 2017).

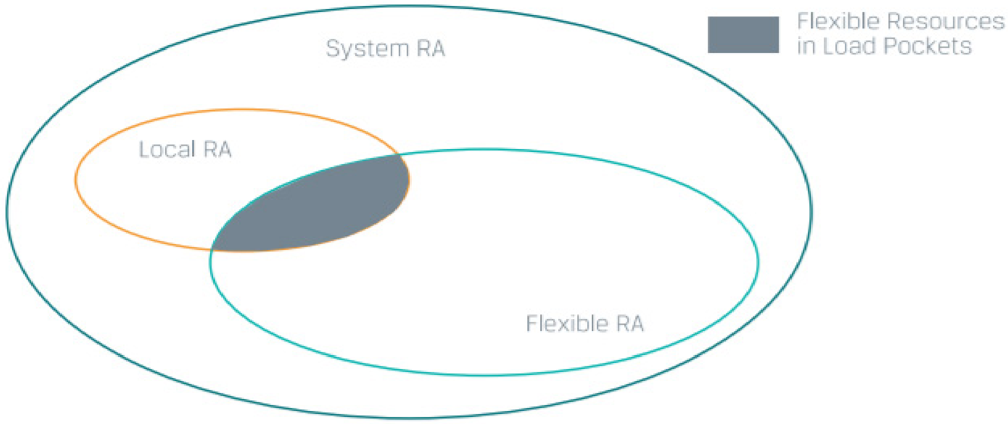


Figure 2.5. CAISO's Annual Resource Adequacy Market Construct

A majority of RA is procured through bilateral agreements between the LSE and the resource owner. A study of 2016 bilateral contracts for RA showed that the weighted average price for all capacity was $3.10/kW-month, although the individual contracts may range from $0.5/kw-month to $35/kw-month (CPUC 2017a). There is not much information available on the Flexible RA contracts. Hence, for the purpose of this study, it is assumed that the PSH may only apply for an RA or LRA contracts with the LSEs.

System and local RA capacity that is contracted for even a single hour in a day is required to be available for dispatch at the qualifying capacity for all 24 hours that day, except for periods of known or forced outages. The resources must submit economic bids for both energy and ancillary services. This is called their "must-offer" obligation.

The RA resources may be dispatched for either energy or ancillary services up to their qualifying capacity, based on CAISOs unit-commitment and economic dispatch processes.

2.1.2.4 NYISO

The NYISO Installed Capacity (ICAP) market is designed to ensure that LSEs have sufficient capacity either on hand or contracted to satisfy both their peak load as well as an 18 percent reserve margin each month. Their individual reserve requirements are determined by demand forecasts of system-coincident peak load in the different load zones. When providing capacity, PSH can be dispatched to supply energy or ancillary services – regulation, spinning reserve, and non-spinning reserve. With the PSH facility qualifying as ICAP capacity, it reduces the region's need for new generation. ICAP capacity is procured by NYISO using annual, monthly, and spot market auctions, as detailed below:

There are three types of capacity auctions that take place within NYISO:

- Capability Period Auction – Occurs 30 days prior to the start of each capability period (summer or winter) where capacity can be bought/sold for the entire capability period;
- Monthly Auction – An auction that occurs monthly where capacity can be bought/sold for the remaining months of the capability period; and
- ICAP Spot Market Auction – Occurs right before the start of each obligation procurement period.

Participation rules for energy-limited resources, as stated in the NYISO Installed Capacity Manual (NYISO 2018):

- "Energy Limited Resources must be able to provide, and provide if scheduled, the Installed Capacity Equivalent of the amount of Unforced Capacity they are supplying to the New York Control Area for a minimum of four (4) hours each day, or for a period of time longer than four (4) hours that is specified by the NYISO after consultation with the Supplier.
- Energy/Capacity Limited Resources must Bid or schedule in the Day-Ahead Market each day in such a way as to enable the NYISO to schedule them for the period in which they are capable of providing the Energy."

The NYISO ICAP demand curve-based reference prices were used to select the optimal amount of capacity to be bid into the ICAP market. The prices for capability period Winter 2017-2018 (NYISO 2018) are presented in Table 2.2.

Table 2.2. NYISO ICAP Reference Prices for Winter 2017-2018

	ICAP Based Reference Points Monthly ($/kW-Month)	**Winter 2017-18 ICAP/UCAP Translation Factor**	**UCAP Based Reference Points Monthly ($/kW-Month)**
	Col. A	*Col. B*	*Col. C = Col. A / (1-Col. B/100)*
NYCA	$9.08	8.43%	$9.92
G-J Locality	$14.84	7.54%	$16.05
NYC	$18.61	5.26%	$19.64
LI	$12.72	6.07%	$13.54

2.1.2.5 Hawaii

For Hawaii, the values were taken from the B&V value of service tables that are equal to the estimated levelized annual cost for the least expensive new peaking plant available on each island. Annual capacity values are presented in Table 2.3 for 2017 through 2031. These costs are extremely high in comparison with the costs evident in the other three regions (CAISO, NYISO, and Pacific Northwest) evaluated under this research program.

To simulate the operation of the PSH during capacity events, the researchers assumed the PSH would be held in reserve from 5pm-9pm each day, and that it would be called upon twice each week for capacity events.

Table 2.3. Capacity Value of Service

Year	**Value of Service ($/kW-Year)**
2017	297.54
2018	303.16
2019	306.78
2020	310.75

Year	Value of Service ($/kW-Year)
2021	314.76
2022	318.68
2023	322.28
2024	326.00
2025	329.44
2026	334.26
2027	339.01
2028	343.45
2029	348.10
2030	352.97
2031	357.56

2.1.3 Regulation Up/Down

2.1.3.1 Regulation Overview

The electric power system must maintain a near real-time balance between generation and load. Balancing generation and load instantaneously and continuously is difficult because loads and generators are constantly fluctuating. Minute-to-minute load variability results from the random turning on and off of millions of individual loads. The services needed to meet such a balancing requirement are referred to as "ancillary services," which are necessary to generate, control, and transmit electricity in support of the basic services of generating capacity, energy supply, and power delivery.

Regulation up/down services are required to continuously balance generation and load under normal conditions. Regulation is the use of online generation, storage, or load that is equipped with automatic generation control (AGC) and that can change output quickly to track the moment-to-moment fluctuations in customer loads and to correct for the unintended fluctuations in generation. Regulation helps to maintain system frequency, manage differences between actual and scheduled power flows between control areas, and match generation to load within the control area. Regulation service has been identified as one of the best "values" from energy storage for increasing grid stability because of the high cost of regulation services.

2.1.3.2 Pacific Northwest

In the Pacific Northwest analysis, regulation prices were obtained from the Northwest Power Pool (NWPP) production cost analysis performed in a previous project (Samaan et al. 2013). The amount of regulation services in each hour is limited by both the power and energy capacities of the SENA Hydro Battery. Such constraints have been modeled in the optimal scheduling process. When regulation services are being called, the hydro battery needs to charge/discharge in order to follow AGC signals. Charging and discharging operations affects the PSH state of charge (SOC). Nevertheless, because regulation signals are small-duration and energy-neutral over time, the cost associated with energy changes in the hydro battery is very small compared to the total revenue from regulation services.

2.1.3.3 CAISO

At CAISO, the regulation value is tied to the capacity bid into the market and the regulation mileage payment. The regulation mileage payment is the compensation to a resource for following the 4-second AGC signal. Regulation mileage is the total amount of regulation service provided by a resource over a 15-minute period. The calculation entails aggregation of the absolute value of all regulation movements, i.e., the sum of absolute values of regulation movement. Imagine a string that is strung up and down on a page. If that string was pulled taut, the entire length of the string would represent the mileage covered by the ESS. Instructed regulation is the sum of all green bars in a 15-minute period, as demonstrated in Figure 2.6.

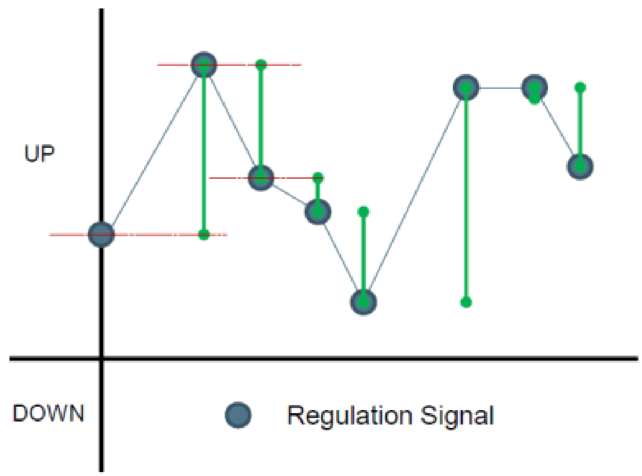


Figure 2.6. Tracking Mileage in the CAISO Regulation Market

CAISO publishes a forecast of regulation mileage requirements, known as a system mileage multiplier (SMM) for the next seven days. The SMMs in conjunction with the regulation mileage prices, for both regulations up and down, for years 2015-2017 were used in the co-optimization problem to obtain the optimal amount of regulation capacity to be bid in any given hour. The SMMs and mileage prices were used to calculate the revenue from provision of regulation service by post-processing in the following manner:

Regulation UP Mileage revenue (hour) = Regulation UP Capacity (hour) * SMM (hour) * Regulation UP Mileage Price

Regulation down is calculated in an identical manner. In this project, regulation prices were obtained from the CAISO market database for each LAP or LMP being evaluated for the time period 2015-2017.

2.1.3.4 NYISO

For the NYISO study, regulation prices were obtained from the NYISO market database for the time period 2015-2017. The analysis for this use case in this location is conducted in the same manner as the Pacific Northwest analysis. That is, the amount of regulation services in each hour is limited by both the power and energy capacities of the SENA Hydro Battery. The battery needs to charge or discharge in order to follow AGC signals whenever it is called upon for regulation services.

2.1.3.5 Hawaii

For the Hawaii analysis, estimated regulation prices, which were obtained from the B&V study for the 2018-2031 time period, were used. Charging and discharging operations affect the PSH SOC. HECO provided a sample regulation signal, as demonstrated in Figure 2.7. Using the two 24-hour signals provided, there are 0.2 MWh up and.01 MWh down needed for each MW service.

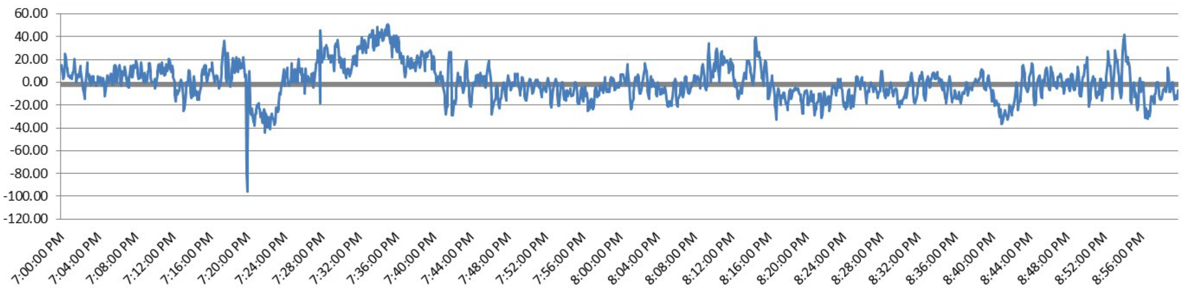


Figure 2.7. HECO Regulation Signal

2.1.4 Frequency Response

2.1.4.1 Basics of Frequency Response

Frequency response is a use case intended to supply energy to maintain stability with regard to the system frequency. It does this by dispatching energy whenever set limits are deviated outside of, keeping load and generation within the system balanced as a result. Frequency response occurs as an event that the ESS must respond to for the entire duration of, failure to do so could lead to imbalances in the system. Though these events typically last for a very small number of total hours throughout a given year, the value obtained from responding to them effectively can be substantial.

2.1.4.2 Pacific Northwest

Under this use case, a Western Electricity Coordinating Council (WECC)-wide frequency response event triggers a required response from northwest utilities. Frequency response events as of yet do not result in notifications by WECC or the North American Electric Reliability Corporation (NERC). Rather, energy storage systems like the Salem Smart Power Center (SSPC) must be set to automatically respond to unexpected frequency excursions. Based on the set points (high and low) established by a frequency regulation screen, the SSPC responded 181 times over 13 months for an average of 13.9 times month. Over roughly 10 months in 2016, PGE registered 18 frequency response events requiring SSPC responses, for an overage of 1.8 events per month. Of these events, the SSPC responded 15 times. Thus, the screen governing the SSPC response successfully responded to a frequency response event 83.3 percent of the time but triggered nearly eight times as many responses as were required by NERC.

Figure 2.8 illustrates a typical frequency response event at the SSPC. The green line represents the power output level by the SSPC during the event. The power output level was around 4 MW over the first four minutes of the event before tapering down to zero. The orange line represents the SOC of the battery over the course of the event, which fell from 80 percent to approximately 54 percent. The red line represents the system frequency, which triggered the response. Notice the droop in system frequency that triggered the event. The entire event required energy over roughly six to seven minutes. PNNL measured the energy output of this event at approximately 300 kWh and PGE validated that the SSPC control algorithm is designed to generate a 300-kWh response. Because the SENA Hydro Battery has the same capacity as the SSPC, the SSPC frequency response discharge profile was used for this market assessment.

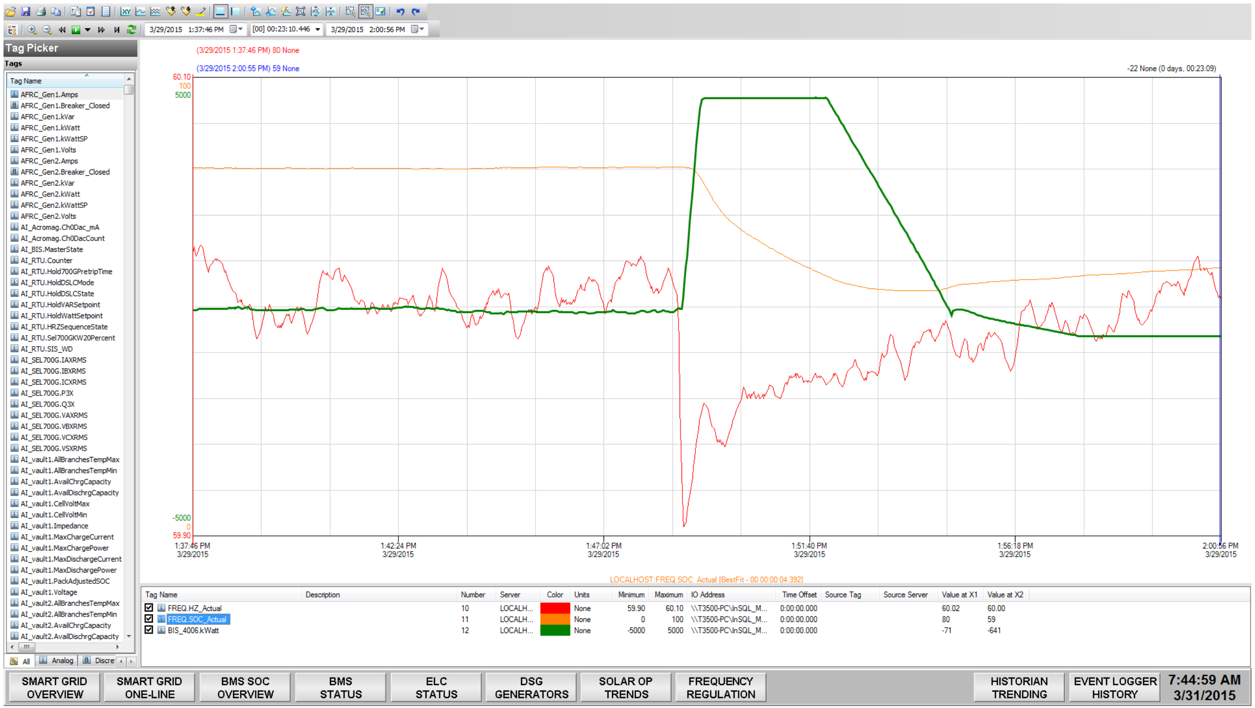


Figure 2.8. Frequency Response Event

In 2016, CAISO contracted with two entities for primary frequency response: Seattle City Light (SCL) and the Bonneville Power Administration (BPA). The SCL contract transfers 15 MW/0.1 hertz (Hz) of frequency regulation to SCL at a contract price of $1.22 million or $81/kW-year (CAISO 2016a). The BPA contract transfers 50 MW/0.1 Hz of frequency regulation to BPA at a contract price of $2.22 million or $44.40/kW-year (CAISO 2016b). The weighted average of these two values ($52.8/kW-year) was used in the market assessment.

PNNL evaluated two cases for primary frequency response. Under the base case, it is assumed that the events cannot be predicted until shortly before they occur, and as a result, 300 kWh of energy must be held in reserve at all times. An alternative case assumes the events can be predicted, thus the need to hold energy in reserve was eliminated for this case.

2.1.4.3 CAISO

Just as in the Pacific Northwest analysis, frequency response events as of yet do not result in notifications by WECC or NERC. Such information was not readily available for the CAISO market, or through the individual IOUs. Hence, to assess the value from provision of primary frequency response service, the information on frequency response events gathered at PGE was used a proxy for all three IOUs in the CAISO territory and the analysis was conducted in the same manner as in the Pacific Northwest.

2.1.4.4 Hawaii

Fast frequency response (FFR) is a response from a generator to a frequency droop at a specified trigger. Under frequency events in this study use the 59.7 Hz threshold. Under frequency events presented in

Table 2.4 were identified by HECO on Oahu for 2017. During these events, PSH would need to supply 5 MW of power for the event duration. With the longest duration of any under frequency event at the 59.5 or 59.7 Hz thresholds registering 9 minutes, 750 kWh of energy must be reserved at all times because there is no event foreknowledge. The value of the FFR service is based on the value of service tables prepared by B&V, which represent the costs avoided if the service were provided at no cost.

Table 2.4. Under Frequency Events on Oahu in 2017 at the 59.7 Hz Threshold

Date	Start Time	Ending Time	Event Duration
2/11/2017	4:22:00 PM	4:24:00 PM	0:02:00
2/13/2017	2:10:00 AM	2:14:00 AM	0:04:00
3/24/2017	5:00:00 PM	5:02:00 PM	0:02:00
3/25/2017	12:36:00 PM	12:38:00 PM	0:02:00
4/9/2017	5:00:00 PM	5:02:00 PM	0:02:00
4/10/2017	4:52:00 PM	4:54:00 PM	0:02:00
4/23/2017	7:21:00 PM	7:23:00 PM	0:02:00
8/21/2017	3:36:00 PM	3:41:00 PM	0:05:00
8/30/2017	3:46:00 PM	3:51:00 PM	0:05:00
9/12/2017	7:08:00 PM	7:15:00 PM	0:07:00
11/28/2017	4:50:00 PM	4:53:00 PM	0:03:00
12/6/2017	8:44:00 PM	8:48:00 PM	0:04:00
12/21/2017	3:32:00 PM	3:36:00 PM	0:04:00
TOTAL		**13**	**0:44:00**

2.1.5 Spin, Non-Spin, and Supplemental Reserves

2.1.5.1 Spin/Non-Spin Reserves

Spin and non-spin reserves are called to restore the generation and load balance in the event of a contingency such as the sudden, unexpected loss of a generator. Any resource that can respond quickly and long enough can supply contingency reserves. Faster response has greater value to the power system.

Spin reserve is provided by power sources already online and synchronized to the grid that can increase output immediately in response to a major generator or transmission outage and can reach full output within 10 minutes. For generators, the spinning reserve is the extra generating capacity that is available by increasing the power output of generators that are already connected to the power system. Unlike regulation up service that is exercised from hour to hour, spinning reserve is not called upon unless the contingency occurs. The frequency that a contingency will occur is very low and can be safely ignored in the economic assessment.

Non-spinning reserve or supplemental reserve is the extra generating capacity that is not currently connected to the system but can be brought online after a short delay. For the hydro battery, it can be modeled the same way as spin reserve.

2.1.5.2 Pacific Northwest

For modeling the Pacific Northwest, both spin and non-spin prices have been obtained from NWPP production cost analysis performed in a previous project (Samaan et al. 2013). Both spin and non-spin reserves are limited by hydro battery power capability. In addition, because it is required that spin and non-spin reserve must sustain the provision of energy for at least an hour, energy capacity puts another constraint on spin and non-spin reserve services.

2.1.5.3 CAISO

For CAISO, both spin and non-spin prices have been obtained from the CAISO market database for the time period 2015-2017. The analysis follows the same procedure as that of the Pacific Northwest in that the hydro battery must provide energy for at least an hour to obtain benefits.

2.1.5.4 NYISO

For NYISO, spin, non-spin, and supplemental reserve prices were obtained from the NYISO market database to conduct the valuation for this use case in this region. The analysis followed the same procedure as both the Pacific Northwest and CAISO analyses.

2.2 Valuation Modeling Approach

BSET was used to run a one-year simulation of hydro battery storage operations. Because the amount of energy stored in a hydro battery is limited, the charging/discharging operation at different time periods is interdependent. For example, injecting more energy into the grid in one hour increases the benefits at that hour, but results in less energy for future use, and may reduce the overall economic benefits. Therefore, the optimal scheduling must be performed over multiple time periods. The hydro battery also has charging/discharging power capacity, for which different grid services may compete against each other. For example, increasing discharging power for energy arbitrage service decreases the battery's capability for other services, such as regulation, spinning, and non-spinning reserve. Moreover, there are losses associated with charging/discharging operations, which must be modeled and considered in the optimal scheduling formulation in order to obtain the maximum obtainable profit. In this evaluation, BSET was used to perform a look-ahead optimization in a 24-hour time window with an hour step over a one-year period. The detailed modeling and formulation of this method can be found in Wu et al. (2015).

The formulation is able to consider the different operation modes of the hydro battery system, including pumping (charging), generating (discharging), spinning reserve, and standby modes. In this formulation, positive power output represents discharging, negative output represents charging, and zero represents either spinning reserve or standby mode. The hydro battery can operate in a spinning reserve mode, providing regulation or spinning reserve with no power output. When not charging, discharging, or operating in spinning reserve mode, the hydro battery system is in standby mode. The static losses in standby mode are approximately 1 percent. Operation in spinning reserve mode results in higher losses—about 3 percent. These static power losses and the associated energy cost are calculated and then removed from the benefits. It should be noted that the hydro battery is also capable of operating in a hybrid mode – i.e., pumping and generating modes at the same time. This can be used for a faster mode switch or to dump extra energy from the system while maintaining a desired SOC level. In this evaluation, fast transition dynamics are not modeled because the time step size is an hour. In addition, dumping energy does not increase benefits of the applications considered in this study. Therefore, the hybrid mode is not engaged.

As described in Section 2.1, each of the four regions included in the analysis contain specific characteristics that define the value the hydro battery is capable of receiving at each location. For this reason, it is necessary to incorporate these characteristics into the battery model to accurately capture all benefit opportunities. The Pacific Northwest and CAISO locations, for example, have access to the Western Energy Imbalance Market (EIM) which offers additional arbitrage opportunities that would not be available to a hydro battery located in NYISO or Hawaii. Likewise, NYISO has its own energy arbitrage opportunities as well as an ICAP market that is unavailable at other locations. Hawaii, on the other hand, is unable to participate in energy markets, however, it has specific opportunities unique to its location such as responding to frequency triggers that can provide significant value. Understanding the unique qualities and opportunities of each region is paramount to accurately modeling and capitalizing on all opportunities.

The economic benefit assessment has been performed for all combinations of bundled services in Section 3.0 for each of the four locations. BSET was used to define the potential economic benefit of the SENA Hydro Battery on an annual basis and to determine the number of hours it would be actively engaged in the provision of each service under optimal conditions.

2.3 Estimated Costs for the SENA Hydro Battery

SENA Hydro Battery cost data were provided by SENA and are summarized in Table 2.5. SENA has estimated a two-year project development cycle consisting of licensing activities in Year 1 and capital costs in Year 2. Licensing costs for the first system are estimated at $3 million, with costs reduced to $1 million for all subsequent plants. The capital cost for the system, excluding the floating membrane, is estimated at $18.7 million (SENA 2017). Debt costs are estimated at $1.5 million, and an additional loan origination fee is estimated at $300,000 (SENA 2017). These costs are estimated with uncertainty at +/- 30 percent. Floating membrane costs are estimated at $600,000 with uncertainty at +100 percent /-50 percent (Steenkamp 2017). Annual operations and maintenance costs are estimated at $408,993 in Year 1 (SENA 2017). Cost estimates also include $1 million in decommissioning costs (Steenkamp 2017). The long-term cost escalation rate is estimated at 2.25 percent (Balducci et al. 2017b). The discount rate is based on the long-term cost of capital estimate of 5.5 percent (SENA 2017). Project life is estimated at 30 years (Steenkamp 2017).

Four cost scenarios are explored in Table 2.5 which are unique to the reference configuration at Pearl Hill, Washington in the Pacific Northwest region analysis. The base case includes all the assumptions outlined in the preceding paragraph. The low-end cost scenario covers the lower end of the ranges of uncertainty around plant and membrane capital costs (minus 30 percent and 50 percent, respectively), while the high-end cost scenario includes 30 percent higher capital costs relative to the base case for plant costs and 100 percent higher membrane costs. The mature system cost scenario, which incorporates learning from licensing and building the first SENA Hydro Battery, includes 30 percent lower capital costs and only $1 million for licensing costs.

Table 2.5. Estimated Costs for SENA Hydro Battery ($Million)

Cost Component	Base	Low-End	High-End	Mature System
Plant Capital	$18.7	$13.1	$24.3	$13.1
Cost of Debt	1.5	1.1	2.0	1.1
Cost of Capital	0.3	0.2	0.4	0.2
Floating Membrane	0.6	0.3	1.2	0.6

Cost Component	Base	Low-End	High-End	Mature System
Licensing	3.0	3.0	3.0	1.0
Decommissioning	1.9	1.9	1.9	1.9
Annual O&M	0.4	0.3	0.5	0.4
Total Life Cycle Costs (PV)	$29.0	$21.2	$37.2	$21.6

In order to accurately estimate the cost for each of the three subsequent regions included in the report, the researchers applied location-specific cost multipliers to the each of the scenarios listed above. These multipliers were based on calibration factors for U.S. city locations by Compass International Inc. and are based on price differences across each location (Compass International, Inc. 2017).

Table 2.6, Table 2.7, and Table 2.8 below show the cost scenarios after the multiplier effect has been applied for CAISO, NYISO, and Hawaii. As an example of how these multipliers are used within a region, for Folsom and Ramona within the CAISO analysis, which both reside within Sacramento and San Diego Counties, a multiplier of 1.14 was applied. The 1.14 multiplier was also used for the SDG&E service territory. For PG&E and SCE, a 1.13 multiplier was applied using the cost location factors for several communities located within each utility's service territory. Note that the multiplier actually represents a combination of two factors – the location factor for each California region (1.07 for Folsom, Ramona, and SDG&E and 1.06 for PG&E and SCE) and a .94 factor applied to the original cost estimate generated for the Pearl Hill, Washington site highlighted in Table 2.5. The .94 factor was assigned based on the location's proximity to Spokane, Washington. The 1.14 multiplier is, therefore, derived by dividing 1.07 by .94.

Table 2.6. Estimated Costs for SENA Hydro Battery in CAISO Areas ($Million)

Location	Cost Multiplier	Base	Low-End	High-End	Mature System
PG&E	1.13	$32.7	$23.9	$41.9	$24.3
SCE	1.13	$32.7	$23.9	$41.9	$24.3
SDG&E	1.14	$33.0	$24.1	$42.3	$24.6
Folsom	1.14	$33.0	$24.1	$42.3	$24.6
Ramona	1.14	$33.0	$24.1	$42.3	$24.6

Table 2.7. Estimated Costs for SENA Hydro Battery in NYISO Areas ($Million)

Location	Cost Multiplier	Base	Low-End	High-End	Mature System
Capital	1.07	$31.20	$22.76	$39.94	$23.23
Central	1.09	$31.51	$22.98	$40.33	$23.46
Dunwood	1.28	$37.07	$27.04	$47.45	$27.60
Genesee	1.12	$32.44	$23.66	$41.52	$24.15
Hudson Valley	1.07	$31.20	$22.76	$39.94	$23.23
Long Island	1.21	$35.22	$25.68	$45.08	$26.22
Mohawk Valley	1.07	$31.20	$22.76	$39.94	$23.23
Millwood	1.07	$31.20	$22.76	$39.94	$23.23
North	1.04	$30.28	$22.08	$38.75	$22.54
NYC	1.28	$37.07	$27.04	$47.45	$27.60

Table 2.8. Estimated Costs for SENA Hydro Battery in Hawaii ($Million)

Location	Cost Multiplier	Base	Low-End	High-End	Mature System
Hawaii	1.22	$35.5	$25.9	$45.5	$26.4

3.0 Economic Results

One of the primary objectives of this research effort is to form a more comprehensive understanding of the value associated with the deployment of the small, modular SENA Hydro Battery. In doing so, the analysis could be useful to not only SENA but also utilities and third-party operators considering alternatives to addressing needs associated with renewables integration, load balancing, or flexible ramping requirements. It is important to note that the basis of some of the values presented in included locations is cost avoidance rather than revenue generation, which is especially the case with the Pacific Northwest and Hawaii analyses. In the CAISO and NYISO markets, on the other hand, most value will be tied to market-driven revenue potential.

3.1 Pacific Northwest

3.1.1 Evaluation of SENA Hydro Battery Benefits and Costs

The first step in estimating the benefits associated with SENA Hydro Battery operation in the Pacific Northwest analysis was to evaluate the benefits of each service individually. Table 3.1 and Figure 3.1 present the results of these individual assessments. The results demonstrate that if the battery was used exclusively for each service, the total value could exceed $55.9 million over 30 years, presented in present value (PV) terms. However, the capacity of the SENA Hydro Battery to generate value is constrained by its operating characteristics and its ability to provide energy when needed for each application. That is, some services are in conflict and cannot be provided simultaneously.

There is competition for the energy in the hydro battery both from an intertemporal and on an application basis. Knowledge of the hydro battery's characteristics and the landscape of economic opportunities matters in terms of optimizing value. To resolve these conflicts, the research team employed BSET. When the model co-optimizes the benefits under the base case, limiting the value to what is technically achievable by the energy storage system, economic value declines to $39.6 million over a 30-year period in PV terms. Note that in the individual assessments, charging costs are embedded in each value. In the co-optimized case, they are reported separately.

The base case scenario, on which the values reported in Table 3.2 are based, employs the following assumptions:

- Arbitrage is run for 2016 using both Mid-C and EIM prices with 300 kWh of energy set aside for primary frequency response events;
- 5 MW of capacity is provided with supplied energy based on historic demand response calls for PGE;
- 5 MW of primary frequency response with 300 kWh of energy set aside at all times for events; and,
- All ancillary services co-optimized with 300 kWh of energy set aside for primary frequency response events.

Table 3.1. Individual vs. Co-Optimized Benefits, Pacific Northwest (30-year PV)

Service	Individual	Co-Optimized
Charging		($5,890,984)
Arbitrage (Mid-Columbia)	$1,008,719	$8,009,055*
Energy Imbalance Market	$3,194,402	
Regulation Up	$14,437,077	$10,609,706
Regulation Down	$7,803,524	$7,645,412
Spin Reserve	$12,126,731	$2,061,796
Non-Spin Reserve	$1,012,194	$832,526
Primary Frequency Response	$4,935,299	$4,935,299
Capacity	$11,389,150	$11,389,150
Total	**$55,907,096**	**$39,591,960**

*The value presented here includes revenue for participation in both the Mid-Columbia and Western EIM. Charging costs were presented separately in the co-optimized case, thus making this value a gross rather than net of charging costs value.

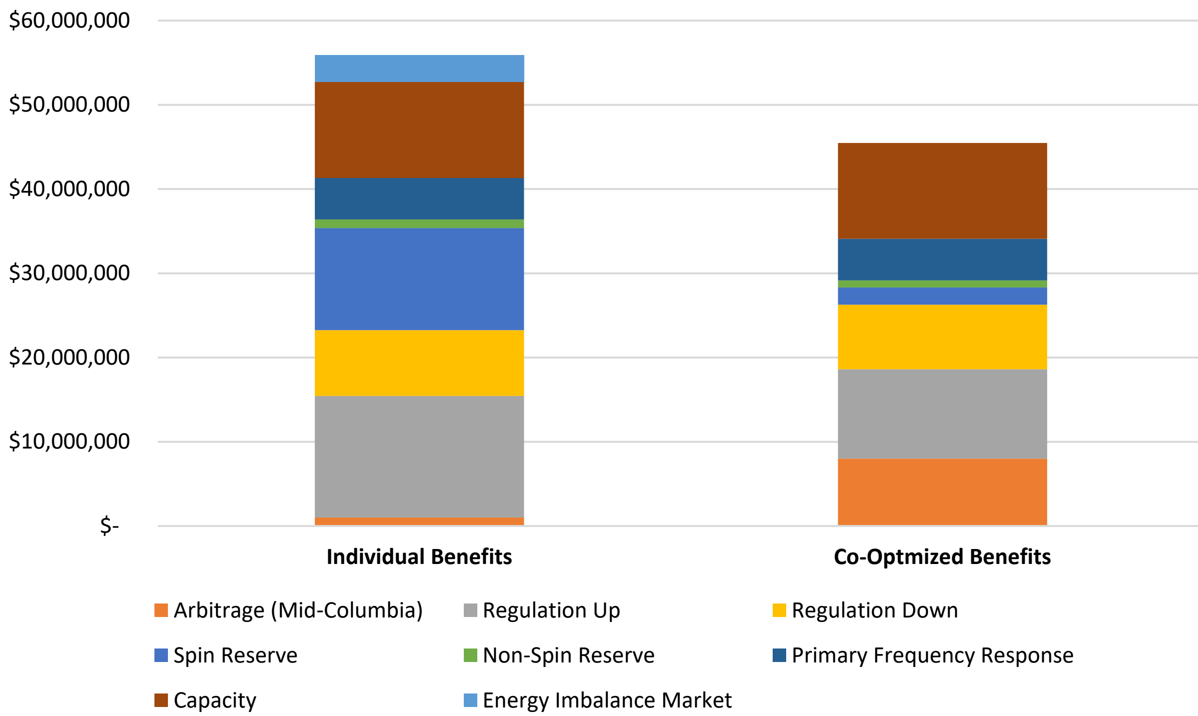


Figure 3.1. Individual Benefits Estimates by Use Case vs. Co-Optimized Benefits, Pacific Northwest

SENA Hydro Battery benefits for the base case ($39.6 million) exceed the costs ($29 million) for the hydro battery (Figure 3.2). The most valuable application is regulation services, which generate nearly $1 million in annual benefits. The hydro battery can provide up to 14 MW of up and down regulation capacity, with 9 MW in pumping capacity and 5 MW in generation capacity. Thus, the hydro battery's ability to provide the service is equivalent to a 7 MW electro-chemical battery system. At that rating, the value of regulation service is estimated at $137/kW-year or $11/kW-month. When all flexibility services (i.e., arbitrage plus ancillary services) are combined, the hydro battery value is estimated at $175/kW-year or $15/kW-month. The value of flexibility services estimated by Puget Sound Energy (PSE) for a PSH systems and PGE for a six-hour energy storage system were recently estimated at $144/kW-year and $63/kW-year (Hossner 2017, Navigant 2017). The second highest value application is capacity at $0.6 million, followed by primary frequency response ($0.3 million), spin/non-spin, and arbitrage.

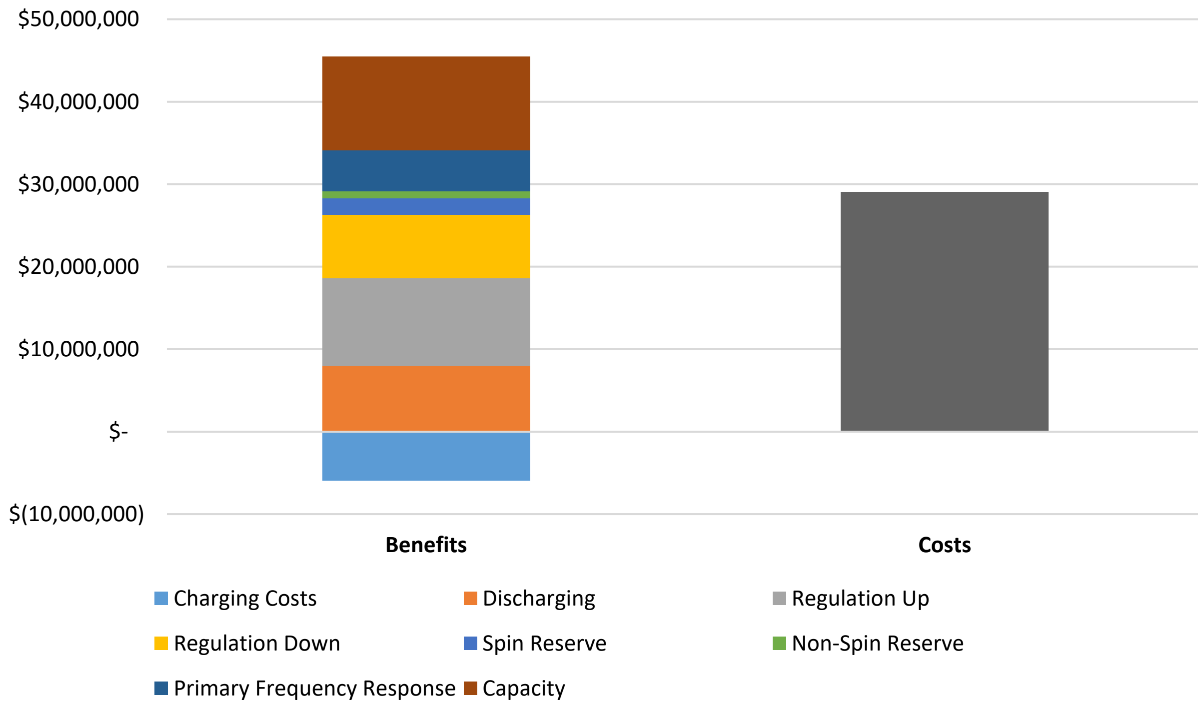


Figure 3.2. Base Case Benefits and Costs for SENA Hydro Battery, Pacific Northwest

3.1.2 Application Hours and Values

Figure 3.3 presents the distribution of annual hours engaged in the provision of each service. Note that in some cases, multiple services would be provided simultaneously. When the ESS is not sitting idle, it is most often engaged in providing arbitrage (3,406 hours), followed by regulation up (2,589 hours), and regulation down (716 hours). Primary frequency response and capacity provide tremendous value despite the fact that those services are concentrated in a very small number of hours each year—17 and 19, respectively.

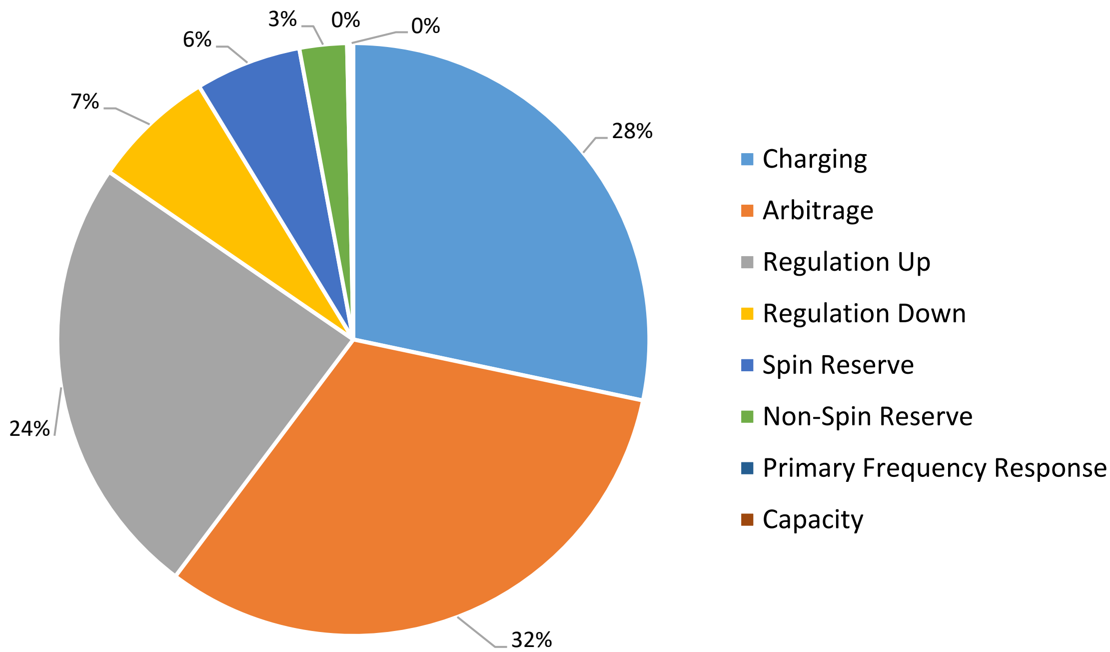


Figure 3.3. Annual Application Hours of the Hydro Battery under the Base Case, Pacific Northwest

3.1.3 Evaluation of Alternative Scenarios and Sensitivity Analysis

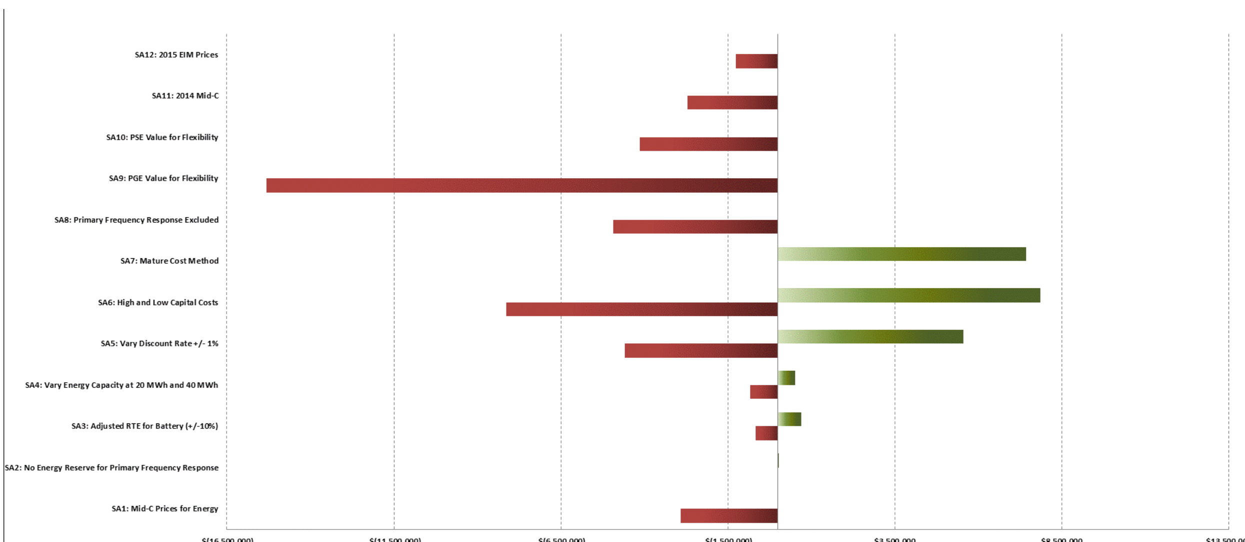
To explore the sensitivity of the results to varying a number of key assumptions, the research team conducted a series of sensitivity analyses. The various scenarios are outlined below, and their impacts were measured in comparison to the base case. Sensitivity analysis (SA) was performed by making the following adjustments to the assumptions:

- SA 1: Mid-Columbia energy prices were used for all charging and arbitrage calculations
- SA 2: No energy reserves for primary frequency response are required
- SA 3: RTE varied between 57.3 percent and 77.3 percent (+/- 10 percent of estimated RTE)
- SA 4: Vary energy capacity at 20 MWh and 40 MWh
- SA 5: Vary discount rate +/- 1 percent
- SA 6: High and low capital costs (+/- 30 percent)
- SA 7: The mature cost method was used
- SA 8: Primary frequency response was excluded as a use case
- SA 9: The PGE value for flexibility was used
- SA 10: The PSE value for flexibility was used
- SA 11: 2014 Mid-Columbia energy prices were used
- SA 12: 2015 EIM energy prices were used

The results of each sensitivity analysis are presented in**Error! Reference source not found.** Figure 3.4. Note the table that appears below the figure. As shown, the changes in energy capacities (SA 4) and reduction in economic life (SA 8) scenarios account for impact on both costs and benefits. All other scenarios evaluate changes only one side of the return on investment (ROI) equation.

Most sensitivity analyses result in negative impacts to the economic results compared to the base case, suggesting that the base case used in this case was not conservative. The most negative impact is revealed in SA10 when PGE-generated values for flexibility were used. Flexibility as defined here includes energy arbitrage, regulation, and spin/non-spin. As noted previously, PGE estimated all flexibility services at $63/kW-year. The value recently estimated by PSE, $144/kW-year, fall much more closely to the estimates prepared by PNNL for this assessment using the PLEXOS model. The results are somewhat sensitive to variations in the discount rate, with a 1 percent adjustment in rate corresponding to roughly +/- $8 million changes in PV benefits. On the positive side, SENA has indicated that after completing the first hydro battery, costs will fall for future deployments as licensing and construction practices evolve and are streamlined. The mature cost method would increase net benefits by $7.4 million over 30 years.

Table 3.2 presents the ROI ratios for the various scenarios defined as part of the sensitivity analysis. The ROI ratio is defined as PV benefits divided by PV costs under each defined scenario. Note that cells shaded yellow have ROI ratios between 0.5 and 1.0 and cells shaded green represent scenarios with ROI ratios in excess of 1.0. When the cost estimates presented by SENA are used in the denominator of the ROI calculations, the vast majority of the explored scenarios yield ROI ratios in excess of 1.0, meaning that PV benefits exceed PV costs. There are exceptions, including several scenarios using the high-cost method and one scenario when the PGE value for flexibility is used in combination with base case costs.



	SA1: Mid-C Prices for Energy	SA2: No Energy Reserve for Primary Frequency Response	SA3: Adjusted RTE for Battery (+/-10%)	SA4: Vary Energy Capacity at 20 MWh and 40 MWh	SA5: Vary Discount Rate +/- 1%	SA6: High and Low Capital Costs	SA7: Mature Cost Method	SA8: Primary Frequency Response Excluded	SA9: PGE Value for Flexibility	SA10: PSE Value for Flexibility	SA11: 2014 Mid-C	SA12: 2015 EIM Prices
Series2		$12,108	$692,805	$519,630	$5,555,272	$7,861,299	$7,422,258					
Low-End	$(2,910,954)		$(671,724)	$(837,460)	$(4,594,749)	$(8,130,835)		$(4,935,299)	$(15,307,213)	$(4,145,846)	$(2,700,615)	$(1,256,382)

Figure 3.4. Sensitivity Analysis Results, Pacific Northwest

Table 3.2. Return on Investment Ratios for Alternative Scenarios, Pacific Northwest

	Base Case	Base Mid-C	No Primary Frequency Response	RTE Down 10 Percentage Points (57.262%)	RTE Up 10 Percentage Points (77.262%)	20 MWh of Capacity
Base	1.36	1.26	1.36	1.34	1.39	1.33
Low Cost Method	1.87	1.73	1.87	1.84	1.90	1.83
High Cost Method	1.07	0.99	1.07	1.05	1.08	1.04
Mature Cost Method	1.83	1.70	1.83	1.80	1.86	1.79

	40 MWh of Capacity	Primary Frequency Response Excluded	PGE Value for Flexibility	PSE Value for Flexibility	2014 Mid-C Prices	2015 EIM Prices
Base	1.38	1.19	0.84	1.22	1.27	1.32
Low Cost Method	1.89	1.64	1.15	1.67	1.74	1.81
High Cost Method	1.08	0.93	0.65	0.95	0.99	1.03
Mature Cost Method	1.86	1.60	1.12	1.64	1.71	1.77

3.2 CAISO

3.2.1 Evaluation of SENA Hydro Battery Benefits and Costs

On an annual basis, the individual values that the included use cases provide are shown in Table 3.3 below. These values are co-optimized, with charging costs embedded into each. Note the high value for primary frequency response in each location despite the low amount of hours for which the battery would be required.

Table 3.3. Annual Individual Values by Use Case and Location, CAISO

	PG&E	SCE	SDG&E	Folsom	Ramona
Arbitrage	$180,434	$190,994	$192,141	$188,288	$273,094
Regulation	$716,118	$712,446	$711,103	$710,848	$681,209
Spin/Non-Spin	$41,359	$40,973	$51,047	$45,606	$46,781
RA Capacity	$35,166	$30,403	$28,221	$35,369	$26,122
Frequency Response	$264,000	$264,000	$264,000	$264,000	$264,000

To estimate 30-year present value benefits for each of the use cases at each of the CAISO locations, energy price growth rates were assigned to each area. The rates used were based on California Public Utility Commission (CPUC) data containing average ¢/kWh rate growths for PG&E, SCE, and SDG&E (CPUC 2017b). The results of these trends yielded the annual growth rates for each of the LAPs presented in Table 3.4.

Table 3.4. Annual Growth Rates for Each LAP within the CAISO Service Area

	Annual Growth Rate
SCE	1.54%
PG&E	3.15%
SDG&E	3.70%

For Folsom and Ramona, the growth rates for their respective LAPs were used for lack of more site-specific growth data. Therefore, Folsom's benefit growth rate was assumed to be 3.15 percent annually and Ramona's growth rate was assumed to be 3.7 percent to match up with their respective LAPs.

The research team used BSET to optimize value subject to both the hydro battery's characteristics as well the landscape of economic opportunities. When the model co-optimizes the benefits under the base case, limiting the value to what is technically achievable by the ESS, the economic values over a 30-year period in PV terms shown in Table 3.5 are achieved.

Table 3.5. Co-Optimized Present Values over 30-Years by Location, CAISO

Location	30-Year Total Co-Optimized Value
PG&E	$26,417,914
SCE	$21,526,062
SDG&E	$28,700,683
Folsom	$26,568,112
Ramona	$29,729,753

The base case scenario, on which the values reported in Table 3.5 are based, employs the following assumptions:

- Energy arbitrage is run for 2015, 2016, and 2017 using the three CAISO LAP prices, assuming perfect foresight. Forecast values are used in a sensitivity analysis scenario which will be described in more detail later.
- 5 MW of primary frequency response with 300 kWh of energy is set aside just in time for the events.
- All ancillary services are co-optimized, up to the RA capacity, which is the result of the optimization itself, along with 300 kWh of energy set aside for primary frequency response events.
- RA capacity price is set at the forecasted price of $2.00/kW-month.
- One set of ancillary services prices are used – assuming perfect foresight. Forecast values are used as a sensitivity analysis in a later section of this report.

The SENA Hydro Battery benefits for the base case do not exceed the costs for any of the CAISO locations as shown in Figure 3.5 below. The location that comes closest to having benefits match costs is the Ramona location, which has $29.7 million in PV benefits versus $33 million in costs, leading to an ROI ratio of.90. The location with the poorest ROI for the base case is the SCE LAP, with $21.5 million in PV benefits and $32.7 million in PV costs.

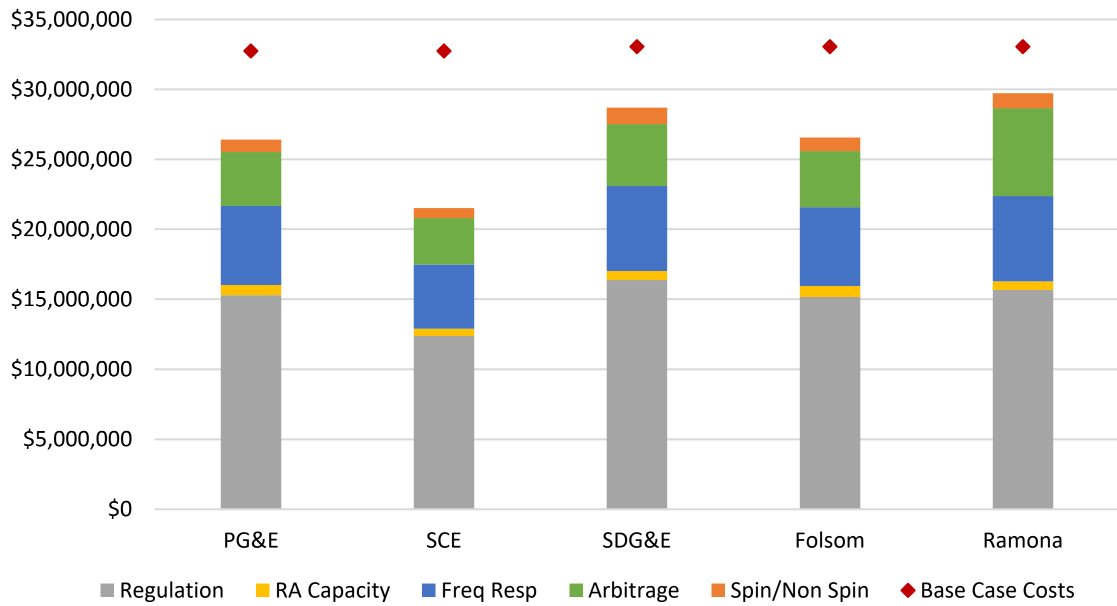


Figure 3.5. Base Case Benefits and Costs for SENA Hydro Battery, CAISO

Table 3.6 below shows the breakdown of individual service contributions to the overall 30-year present values reported for each location. SENA Hydro Battery benefits for the base case fall short of the associated costs (Figure 3.6) in all CAISO locations when an RA price of $2/kW-month is assumed. The most valuable application in all cases is regulation services, which generate approximately $700,000 in annual benefits for each project. When all flexibility services (i.e., arbitrage plus ancillary services) are combined, the hydro battery value is estimated at approximately $0.9-$1.0 million annually. The second-highest value application is primary frequency response at approximately $264,000 annually, and finally arbitrage and spin/non-spin.

Table 3.6. Individual 30-year Co-Optimized Present Values by Use Case, CAISO

Service	PG&E	SCE	SDG&E	Folsom	Ramona
RA Capacity	$750,973	$528,284	$649,785	$755,309	$601,444
Arbitrage	$3,853,192	$3,318,776	$4,423,996	$4,020,904	$6,287,935
Regulation	$15,292,767	$12,379,687	$16,372,998	$15,180,235	$15,684,703
Spin Reserve/Non-Spin Reserve	$883,236	$711,964	$1,175,357	$973,917	$1,077,124
Primary Frequency Response	$5,637,747	$4,587,350	$6,078,547	$5,637,747	$6,078,547
Total	**$26,417,914**	**$21,526,062**	**$28,700,683**	**$26,568,112**	**$29,729,753**

Figure 3.6 presents the PV benefits and costs for all locations using the mature cost values. These values are more representative of a mature and well-developed SENA Hydro Battery, and as such are useful for determining the ROI associated with the system once fully developed. Benefits exceed costs in all locations with the exception of SCE, which only increased its ROI from .66 to .88 for the base case. Ramona has the highest ROI under this scenario at 1.21, followed by SDG&E at 1.17.

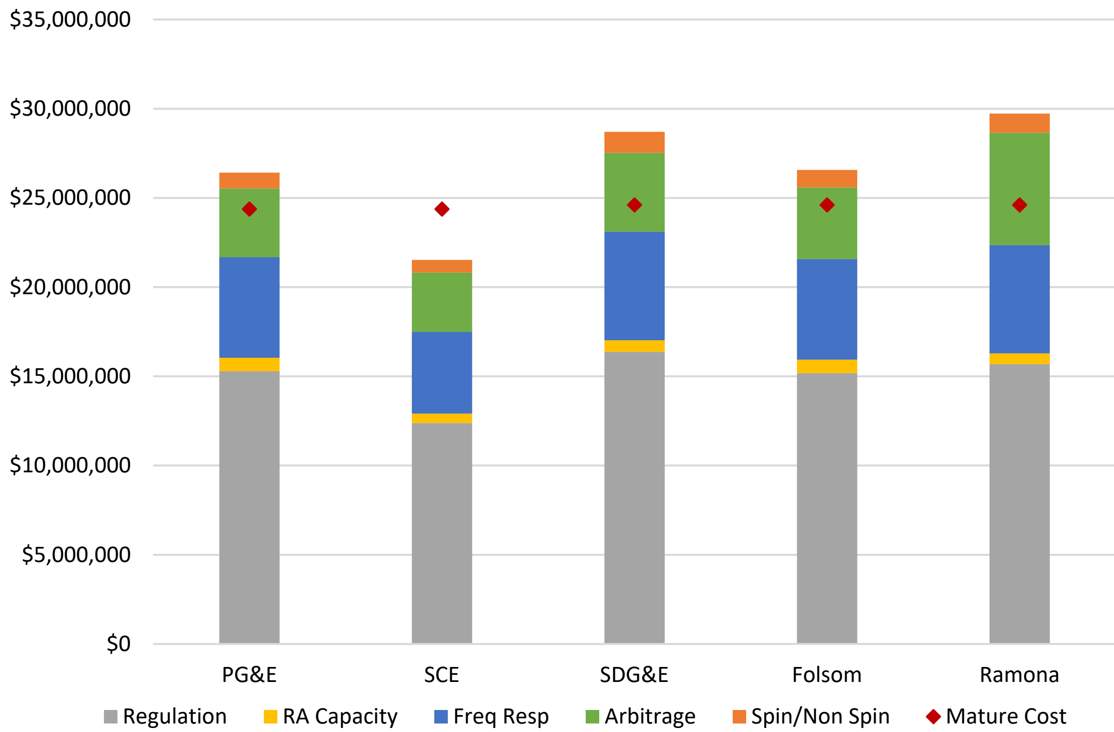


Figure 3.6. 30-Year Individual Present Value Benefits vs. Costs by Location – Mature Cost Method, CAISO

3.2.2 Application Hours and Values

Figure 3.7 presents the annual hours engaged in the provision of each service. Note that in some cases, multiple services would be provided simultaneously. When the ESS is not sitting idle, it is most often engaged in providing regulation down (7,903 hours on average), followed by regulation up (1,845 hours on average), and discharging to partake in arbitrage (1,754 hours on average). Primary frequency response provided tremendous value despite the fact that the service is concentrated in 13 hours each year.

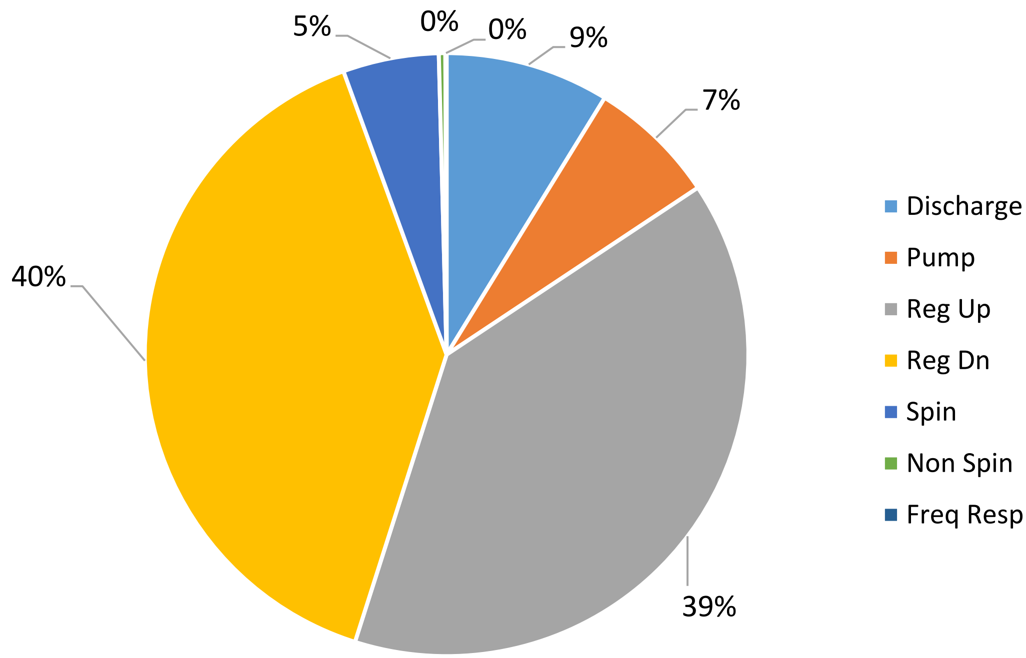


Figure 3.7. Average Annual Application Hours of the Hydro Battery Across All CAISO Locations Under the Base Case

3.2.3 Evaluation of Alternative Scenarios and Sensitivity Analysis

To explore the sensitivity of the results to varying a number of key assumptions, the research team conducted a series of sensitivity analyses. The various scenarios are outlined below and their impacts were measured in comparison to the base case. Sensitivity analysis was performed by making the following adjustments to the assumptions:

- SA 1: No Primary Frequency Response Included
- SA 2: +/- 1% Discount Rate
- SA 3: Low Cost Method
- SA 4: High Cost Method
- SA 5: Mature Cost Method
- SA 6: Forecast Prices Used
- SA 7: $0.50/kW-Month Resource Adequacy Price
- SA 8: $5/kW-Month Resource Adequacy Price
- SA 9: $12.50/kW-Month Resource Adequacy Price

The results of each sensitivity analysis are presented in Figure 3.8. As shown, the changes in discount rate account for impacts on both costs and benefits. All other scenarios evaluate changes only on one side of the ROI equation.

The sensitivity analyses offer both negative and positive impacts to the economic results compared to the base case. The most negative impact is revealed in SA4 when the High Cost method was used. The high cost scenario, as mentioned before, includes 30 percent higher capital costs relative to the base case for plant costs and 100 percent higher membrane costs. The results are mildly sensitive to variation in the rate with a positive and negative increase of approximately $2 million on average for each location. On the positive side, the mature cost method, which would appear as future deployments of energy storage leads to a more streamlined and cost-effective process, resulted in an approximate $8 million increase on average over 30 years for each location.

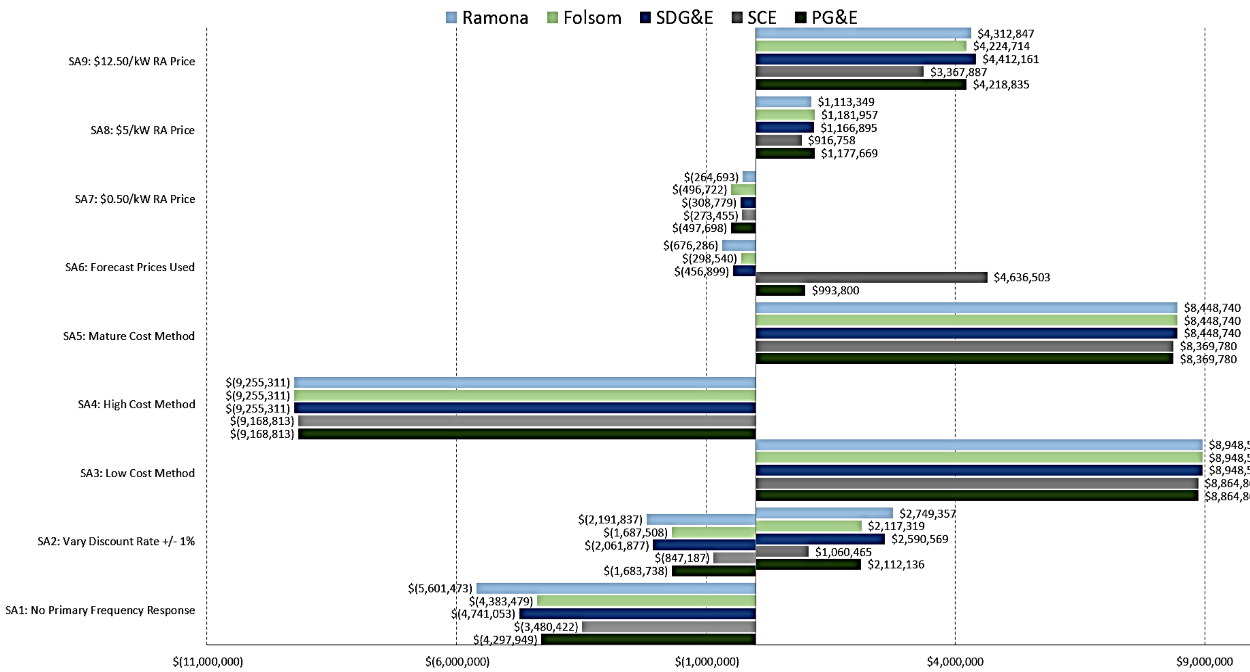


Figure 3.8. Sensitivity Analysis Results, CAISO

Table 3.7 presents the ROI ratios for the various scenarios as part of the sensitivity analysis. When the low cost and mature cost estimates presented by SENA are used in the denominator of the ROI calculations, the vast majority of the explored scenarios yield ROI ratios in excess of 1.0, meaning that PV benefits exceed PV costs. SCE is the only exception in this scenario, which returns ROIs of .90 and .88 for the low cost and mature cost scenarios, respectively. No scenarios result in an ROI of less than .50; however, no scenarios, other than the low cost, mature cost, and $12.50/kW-month RA price scenarios, resulted in ROI values greater than 1.0.

Table 3.7. ROI Ratios for Alternative Scenarios, CAISO

	Base Case	Forecast Price Values	Low Cost	High Cost	Mature Cost
PG&E	0.81	0.84	1.11	0.63	1.08
SCE	0.66	0.80	0.90	0.51	0.88
SDG&E	0.87	0.85	1.19	0.68	1.17
Folsom	0.80	0.79	1.10	0.63	1.08
Ramona	0.90	0.88	1.23	0.70	1.21

	Primary Frequency Response Excluded	$0.50/kW-Month Resource Adequacy Price	$5/kW-Month Resource Adequacy Price	$12.50/kW-Month Resource Adequacy Price	-1% Discount Rate	+1% Discount Rate
PG&E	0.68	0.79	0.84	0.94	0.74	0.88
SCE	0.55	0.65	0.69	0.76	0.61	0.71
SDG&E	0.72	0.86	0.90	1.00	0.80	0.95
Folsom	0.67	0.79	0.84	0.93	0.74	0.87
Ramona	0.73	0.89	0.93	1.03	0.82	0.98

3.3 NYISO

3.3.1 Evaluation of SENA Hydro Battery Benefits and Costs

On an annual basis, the individual values that the included use cases provide are shown in Table 3.8 below. These values are co-optimized with charging costs embedded into each. Because all charging costs, regardless if the energy is used for arbitrage, are embedded in these values, the estimate runs negative in the Capital Zone. The annual revenue varies from a low of $1.3 million in the Capital Zone to $1.9 million annually in the NYC Zone. The largest source of revenue is tied to the ICAP, followed by regulation services.

Table 3.8. Annual Individual Values by Use Case and Location, NYISO

	Arbitrage	Regulation	Spin/Non-Spin	ICAP Revenue	Total
Capital	-$13,100	$487,518	$218,526	$603,966	$1,296,910
Central	$32,991	$484,221	$199,102	$603,966	$1,320,281
Dunwood	$16,831	$486,290	$215,931	$914,186	$1,633,238
Genesee	$28,822	$486,185	$199,513	$603,966	$1,318,486
Hudson Valley	$9,438	$485,846	$216,703	$914,186	$1,626,173
Long Island	$62,059	$473,070	$213,706	$719,093	$1,467,928
Mohawk Valley	$29,059	$482,939	$199,968	$603,966	$1,315,931
Millwood	$11,687	$486,741	$217,157	$914,186	$1,629,771
North	$22,669	$481,280	$202,965	$603,966	$1,310,880
NYC	$23,489	$481,632	$214,197	$1,195,273	$1,914,591

To estimate 30-year PV benefits for each of the use cases at each of the NYISO locations, growth rates specific to NYC (1.3 percent) and the remainder of the state (2.9 percent) were estimated. The rates used were based on Navigant's 2017 Energy Market Outlook (Patrylak 2017) and are presented in Table 3.9.

Table 3.9. Annual Growth Rates for NYISO by Location

	Annual Growth Rate
New York City	1.3%
Rest of State	2.9%

Applying the growth rates in Table 3.9 and the aforementioned 5.5 percent discount rate results in the 30-year PV benefit estimates presented in Table 3.10.

Table 3.10. Co-Optimized Present Values over 30-Years by Location, NYISO

Location	**30-Year Total Co-Optimized Value**
Capital	$26,786,273
Central	$27,268,973
Dunwood	$33,732,778
Genesee	$27,231,909
Hudson Valley	$33,586,851
Long Island	$30,318,474
Mohawk Valley	$27,179,136
Millwood	$33,661,168
North	$27,074,813
NYC	$32,317,816

The base case scenario, on which the values reported in Table 3.8 and Table 3.10 are based, employs the following assumptions:

- Energy arbitrage is run for 2015, 2016, and 2017 using the 10 NYISO zonal prices, assuming both perfect foresight, and forecast values, where

Forecast price (hour *h*) = Average price over previous week at hour *h*

The forecast was done differently for weekend vs. weekday hours. For a weekend hour *h*, the forecast price was obtained by taking the average of the past week's prices at hour *h.* Similarly, for a weekend hour *h,* the forecast price was obtained by taking the average of previous week's prices at hour *h.* The averaging of prices to obtain the forecast was done using the sliding-window process. For instance,

Forecast price for hour *h* on Tuesday (Day *d*) = Average (Tuesday (*d*-7), Wednesday (*d*-6), Thursday (*d*-5), Friday (*d*-4), Monday (*d*-1)) of prices (hour *h*).

Similarly,

Forecast for hour *h* on Saturday (Day *d*) = Average (Sunday (*d*-1), Saturday (*d*-7)) of prices (hour *h*).

The perfect foresight prices were derived by using the time-series of prices for a given year. The methodology was applied to all ancillary services. The revenues estimated using the assumption of perfect foresight constituted the base cases for all the zones, while the forecast prices were used to conduct the sensitivity analyses.

- All ancillary services are co-optimized,
- ICAP capacity prices are based on NYISO's reference prices for the year 2017, and
- It is assumed that the ICAP capacity is called into service by NYISO for a) top 5% loading hours, b) top 10% loading hours, c) top 20% loading hours, and d) all days loading hours, with a minimum power output at the ICAP capacity level for a 4-hour duration.

The SENA Hydro Battery benefits for the base case do not exceed the costs for all but two of the NYISO locations as shown in Figure 3.9 below. The two locations in which benefits exceed costs are Hudson Valley and Millwood, both with approximately $33.6 million in benefits and $31.2 million in costs. The location with the lowest ROI for the base case is Genesee, with $27.2 million in PV benefits and $32.4 million in PV costs.

Table 3.11 below shows the breakdown of individual service contribution to the overall 30-year present values reported for each location in Table 3.10. The most valuable application is ICAP capacity, which generates over $15 million in 30-year PV benefits on average across zones, followed by regulation services, which generate nearly $.5 million in annual benefits and approximately $9.8 million on average in 30-year PV benefits.

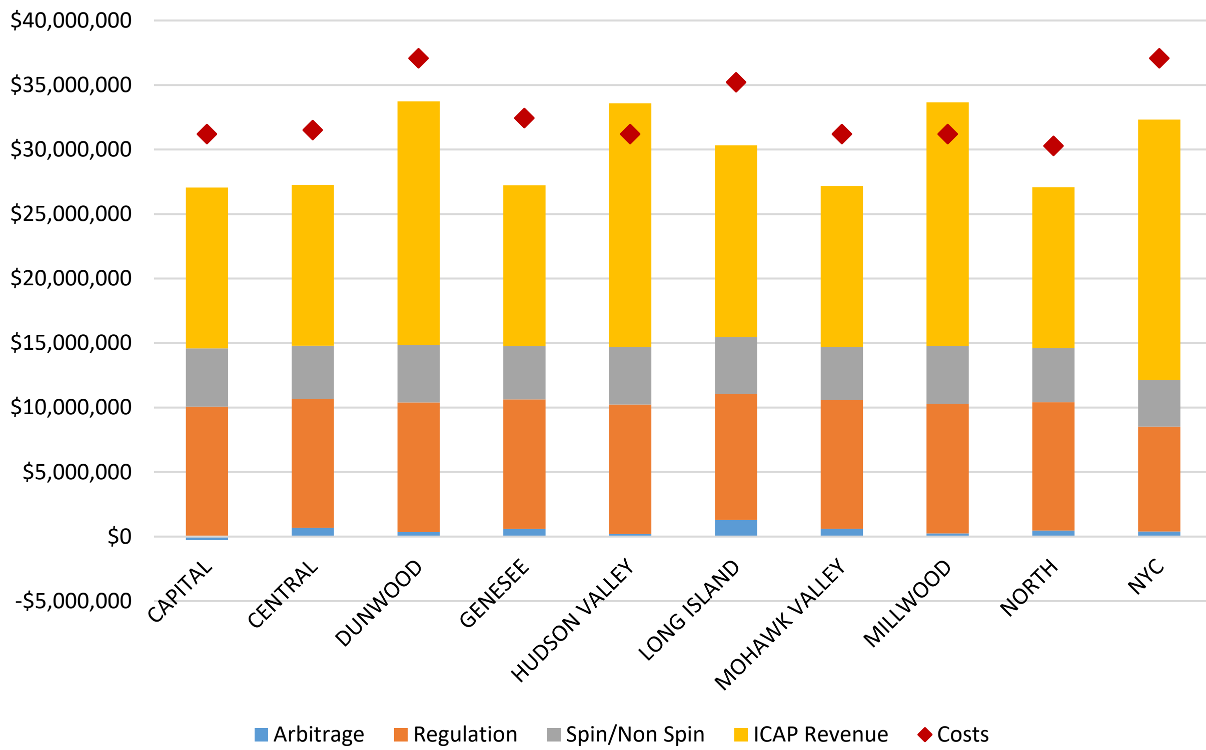


Figure 3.9. 30-Year Net Present Value Benefits and Costs for SENA Hydro Battery by Location, Base Case, NYISO

Table 3.11. Individual 30-year Co-Optimized Present Values by Use Case, NYISO

	Capital	Central	Dunwood	Genesee	Hudson Valley
Arbitrage	-$270,565	$681,404	$347,626	$595,297	$194,922
Regulation	$10,069,166	$10,001,072	$10,043,796	$10,041,628	$10,034,635
Spin/Non-Spin	$4,513,417	$4,112,242	$4,459,831	$4,120,729	$4,475,770
ICAP Revenue	$12,474,256	$12,474,256	$18,881,525	$12,474,256	$18,881,525
Total	$26,786,273	$27,268,973	$33,732,778	$27,231,909	$33,586,851
	Long Island	**Mohawk Valley**	**Millwood**	**North**	**NYC**
Arbitrage	$1,281,760	$600,180	$241,383	$468,203	$396,496
Regulation	$9,770,755	$9,974,583	$10,053,108	$9,940,321	$8,129,821
Spin/Non-Spin	$4,413,876	$4,130,117	$4,485,152	$4,192,033	$3,615,590
ICAP Revenue	$14,852,083	$12,474,256	$18,881,525	$12,474,256	$20,175,909
Total	$30,318,474	$27,179,136	$33,661,168	$27,074,813	$32,317,816

The results presented in Figure 3.9 and Table 3.11 use the base case costs. Figure 3.10 presents the PV benefits and costs for all locations using the mature cost values. These values are more representative of a mature and well-developed SENA Hydro Battery, and as such are useful for determining the ROI associated with the system once fully developed. Benefits exceed costs in all locations with ROI ratios ranging from a low of 1.13 in Genesee to 1.45 in Hudson Valley and Millwood.

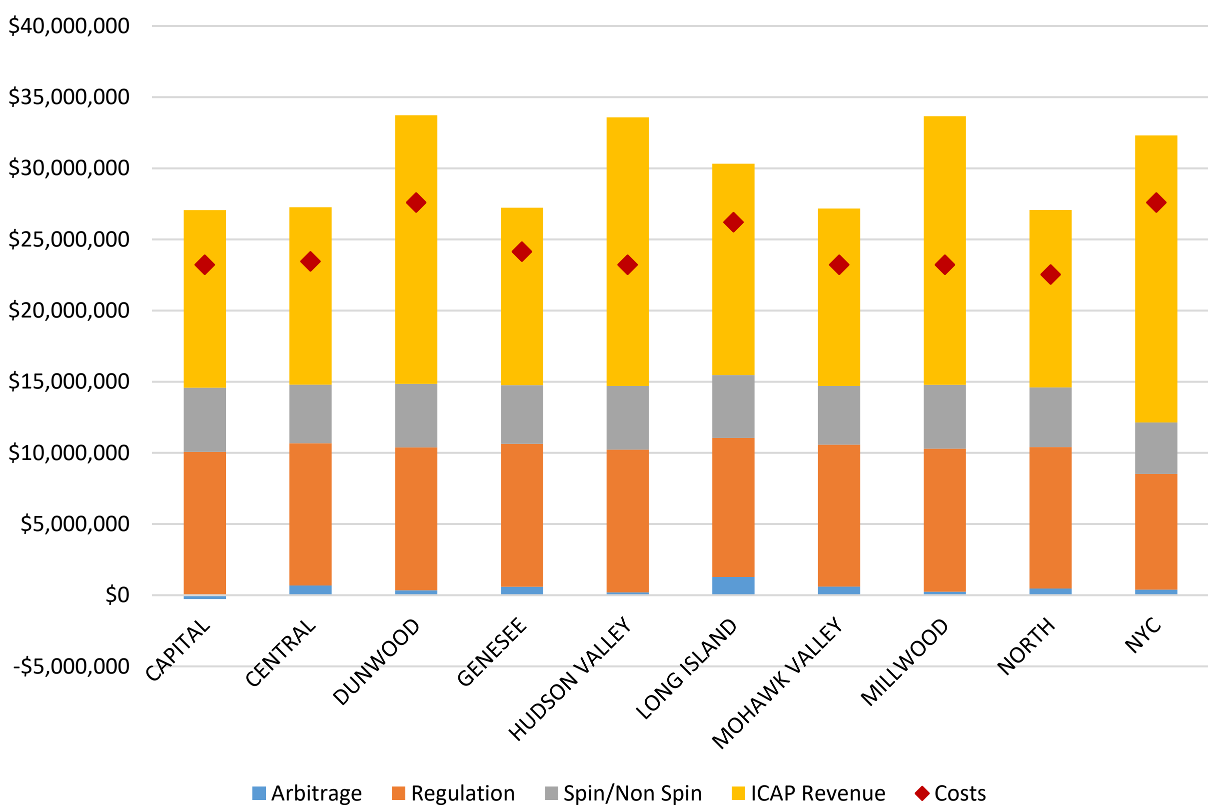


Figure 3.10. 30-Year Net Present Benefits and Costs for SENA Hydro Battery by Location, Mature Case, NYISO

Figure 3.11 presents the annual hours engaged in the provision of each service. Note that in some cases, multiple services would be provided simultaneously. When the ESS is not sitting idle, it is most often engaged in providing regulation services (7,117 hours on average, 32 percent), followed by pumping (6,032 hours on average, 27 percent), and spin services (4,675 hours on average, 21 percent). ICAP revenue provides tremendous value despite the fact that the service is only 7 percent of the overall time allocation.

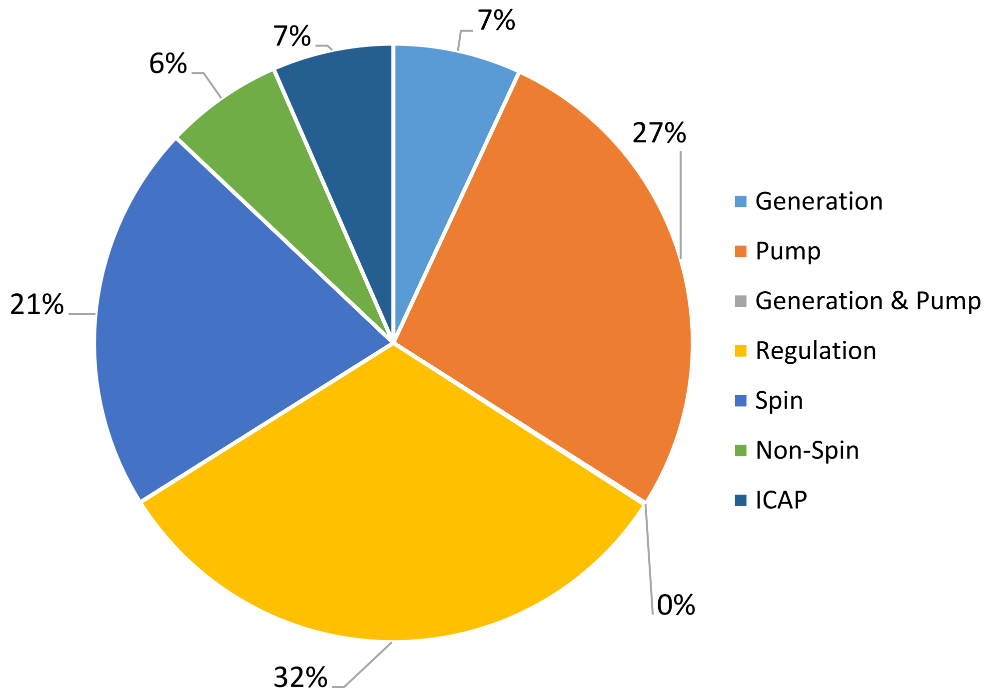


Figure 3.11. Average Application Percent of Total Hours of the Hydro Battery on an Annual Basis, NYISO

3.3.2 Evaluation of Alternative Scenarios and Sensitivity Analysis

To explore the sensitivity of the results to varying a number of key assumptions, the research team conducted a series of sensitivity analyses. The various scenarios are outlined below and their impacts were measured in comparison to the base case. Sensitivity analysis was performed by making the following adjustments to the assumptions:

- SA 1: +/- 1% Discount Rate
- SA 2: Low Cost Method
- SA 3: High Cost Method
- SA 4: Mature Cost Method
- SA 5: Top 5% Loading Hours
- SA 6: Top 10% Loading Hours
- SA 7: Top 20% Loading Hours
- SA 8: Forecast Prices Used Rather than Assuming Perfect Foreknowledge

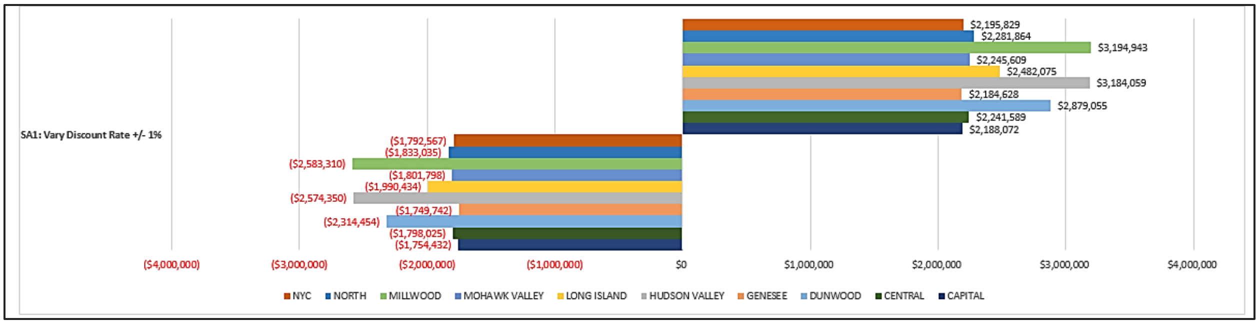
NYISO's ICAP market rules require the resources that were cleared in the capacity auctions to provide, if scheduled, installed capacity equivalents for a minimum of four hours each day. However, the resources may not be scheduled every day, or for all four hours. Moreover, to the authors' best knowledge, the information on scheduling of ICAP resources is not published explicitly by NYISO. Hence, to satisfy the market rules pursuant to participation in the ICAP market, it was assumed that the SENA battery could be called for a certain percentage of the hours in a year. The three sensitivity analysis cases were designed presuming that the SENA battery would be called to produce energy (discharge) only for four consecutive hours on a given day. The selection of hours was done by analyzing the hourly system load in a given year, and identifying 5, 10, and 20 percent of the highest load hours. The 4-hour block for the SENA battery to discharge started on the highest loaded hour day. The process, algorithmically, may be described as follows:

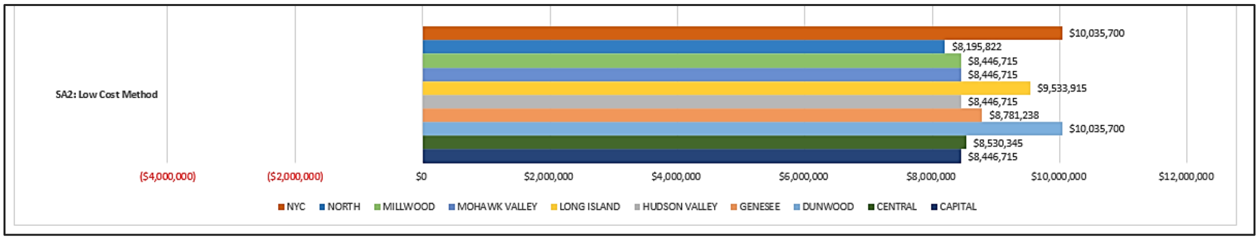
1. Sort the hours (8,760), in descending order of hourly load
2. Identify the X percent of the sorted list
3. Identify the 4-hour block for a given day, starting the highest loaded hour for the day

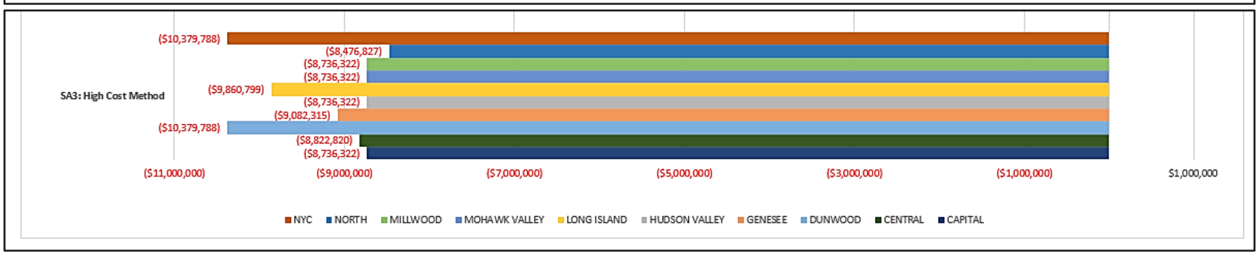
The co-optimization formulation in BSET, for NYISO, was modified to account for the amount of energy needed by the SENA battery to discharge up to the ICAP capacity during the 4-hour blocks.

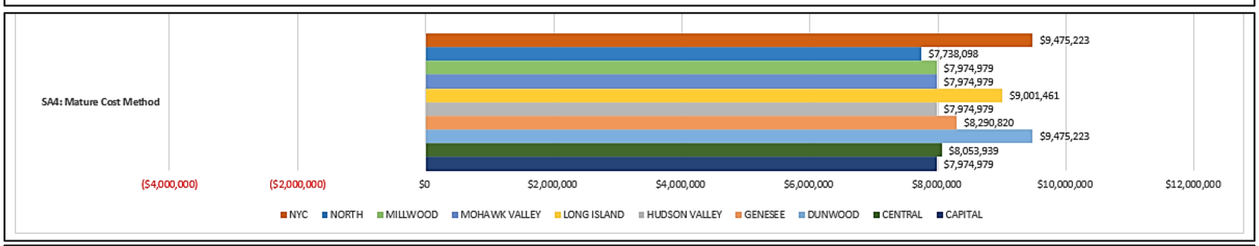
The results of each sensitivity analysis are presented in Figure 3.12. As shown, the changes in discount rate impacts both costs and benefits. All other scenarios evaluate changes only on one side of the ROI equation.

The sensitivity analyses offer both negative and positive impacts to the economic results compared to the base case. The highest negative impact is revealed in SA3 when the high-cost method was used. The high-cost scenario, as mentioned before, includes 30 percent higher capital costs relative to the base case for plant costs and 100 percent higher membrane costs. The results are only mildly sensitive to variation in the discount rate, with a positive and negative increase of approximately $2 million on average for each location. On the positive side, the mature cost method, which would appear as future deployments of energy storage lead to a more streamlined and cost-effective process, resulted in an approximate $8 million increase in net benefits on average over 30 years for each location. The variations in adjusting top loading percent all had minor positive impacts on the results, averaging less than $1 million in additional benefits in each case and location.


SA1: Vary Discount Rate +/- 1%
$2,195,829
$2,281,864
$3,194,943
$2,245,609
$2,482,075
$3,184,059
$2,184,628
$2,879,055
$2,241,589
$2,188,072
($1,792,567)
($1,833,035)
($2,583,310)
($1,801,798)
($1,990,434)
($2,574,350)
($1,749,742)
($2,314,454)
($1,798,025)
($1,754,432)
($4,000,000)
($3,000,000)
($2,000,000)
($1,000,000)
$0
$1,000,000
$2,000,000
$3,000,000
$4,000,000
NYC
NORTH
MILLWOOD
MOHAWK VALLEY
LONG ISLAND
HUDSON VALLEY
GENESEE
DUNWOOD
CENTRAL
CAPITAL


SA2: Low Cost Method
$10,035,700
$8,195,822
$8,446,715
$8,446,715
$9,533,915
$8,446,715
$8,781,238
$10,035,700
$8,530,345
$8,446,715
($4,000,000)
($2,000,000)
$0
$2,000,000
$4,000,000
$6,000,000
$8,000,000
$10,000,000
$12,000,000
NYC
NORTH
MILLWOOD
MOHAWK VALLEY
LONG ISLAND
HUDSON VALLEY
GENESEE
DUNWOOD
CENTRAL
CAPITAL


SA3: High Cost Method
($10,379,788)
($8,476,827)
($8,736,322)
($8,736,322)
($9,860,799)
($8,736,322)
($9,082,315)
($10,379,788)
($8,822,820)
($8,736,322)
($11,000,000)
($9,000,000)
($7,000,000)
($5,000,000)
($3,000,000)
($1,000,000)
$1,000,000
NYC
NORTH
MILLWOOD
MOHAWK VALLEY
LONG ISLAND
HUDSON VALLEY
GENESEE
DUNWOOD
CENTRAL
CAPITAL


SA4: Mature Cost Method
$9,475,223
$7,738,098
$7,974,979
$7,974,979
$9,001,461
$7,974,979
$8,290,820
$9,475,223
$8,053,939
$7,974,979
($4,000,000)
($2,000,000)
$0
$2,000,000
$4,000,000
$6,000,000
$8,000,000
$10,000,000
$12,000,000
NYC
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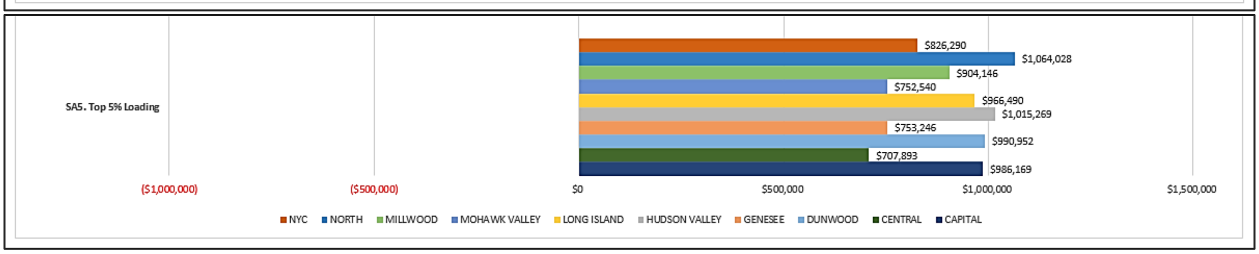
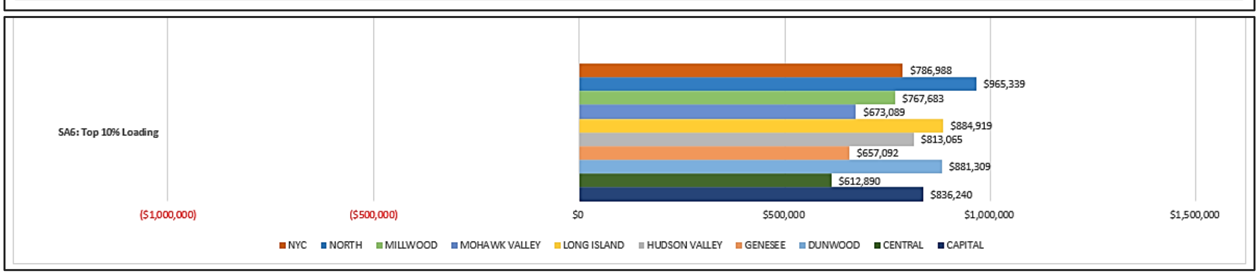

SA5. Top 5% Loading
$826,290
$1,064,028
$904,146
$752,540
$966,490
$1,015,269
$753,246
$990,952
$707,893
$986,169
($1,000,000)
($500,000)
$0
$500,000
$1,000,000
$1,500,000
NYC
NORTH
MILLWOOD
MOHAWK VALLEY
LONG ISLAND
HUDSON VALLEY
GENESEE
DUNWOOD
CENTRAL
CAPITAL


SA6: Top 10% Loading
$786,988
$965,339
$767,683
$673,089
$884,919
$813,065
$657,092
$881,309
$612,890
$836,240
($1,000,000)
($500,000)
$0
$500,000
$1,000,000
$1,500,000
NYC
NORTH
MILLWOOD
MOHAWK VALLEY
LONG ISLAND
HUDSON VALLEY
GENESEE
DUNWOOD
CENTRAL
CAPITAL

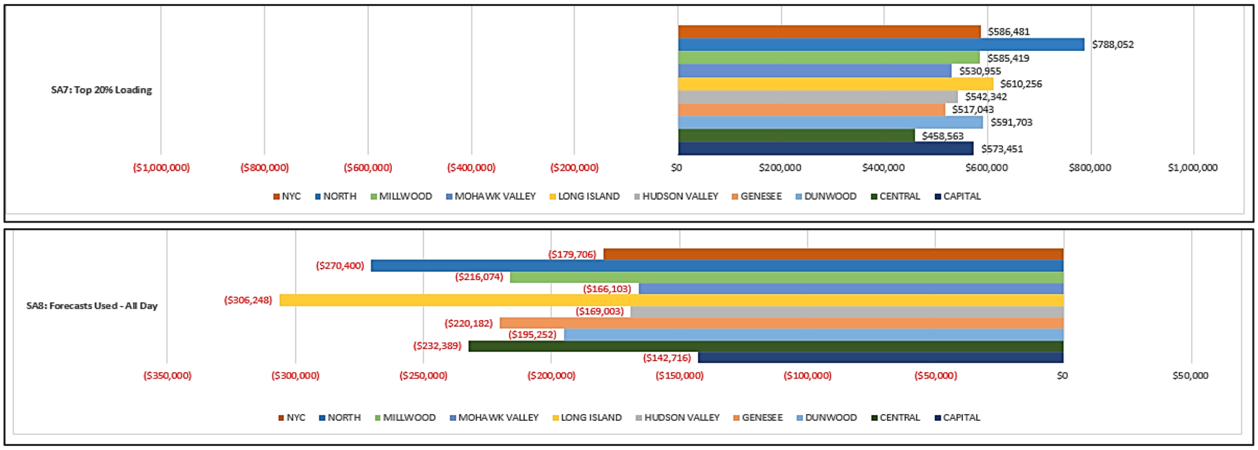


Figure 3.12. Sensitivity Analysis Results, NYISO

Table 3.12 presents the ROI ratios for the various scenarios as part of the sensitivity analysis. When the low-cost and mature-cost estimates presented by SENA are used in the denominator of the ROI calculations, all locations yield ROI ratios in excess of 1.0. Other positive returns are found in Hudson Valley and Millwood for each of the top loading percent scenarios explored as well as the forecast values scenario.

Table 3.12. Benefit-Cost Ratios for Alternative Sensitivity Analysis Scenarios, NYISO

	Base Case	Low Cost	High Cost	Mature Cost	+1% DR	-1% DR
Capital	0.86	1.18	0.67	1.15	0.79	0.97
Central	0.87	1.19	0.68	1.16	0.80	0.96
Dunwood	0.91	1.25	0.71	1.22	0.84	0.91
Genesee	0.84	1.15	0.66	1.13	0.77	0.99
Hudson Valley	1.08	1.48	0.84	1.45	0.99	0.77
Long Island	0.86	1.18	0.67	1.16	0.79	0.97
Mohawk Valley	0.87	1.19	0.68	1.17	0.80	0.95
Millwood	1.08	1.48	0.84	1.45	0.99	0.77
North	0.89	1.23	0.70	1.20	0.83	0.93
NYC	0.87	1.20	0.68	1.17	0.81	0.97

	Top Loading Percent			
	5%	10%	20%	Forecast Values
Capital	0.89	0.89	0.88	0.85
Central	0.89	0.88	0.88	0.86
Dunwood	0.94	0.93	0.93	0.90
Genesee	0.86	0.86	0.86	0.83
Hudson Valley	1.11	1.10	1.09	1.07
Long Island	0.89	0.89	0.88	0.85
Mohawk Valley	0.90	0.89	0.89	0.87
Millwood	1.11	1.10	1.10	1.07
North	0.93	0.93	0.92	0.89
NYC	0.89	0.89	0.89	0.87

3.4 Hawaii

3.4.1 Evaluation of SENA Hydro Battery Benefits and Costs

The 30-year present value benefits for PSH on Oahu are presented in Table 3.13. These values are co-optimized with charging costs embedded into each service. The largest benefit is tied to capacity, which reaches over $300/kW-year in 2018, and totals $25.3 million over the 30-year PSH lifecycle. Capacity is followed by regulation reserve ($8.5 million), arbitrage ($7.44 million), and FFR ($20,924). Total benefits are estimated at $41.3 million over the 30-year PSH lifecycle.

Table 3.13. Annual Individual Values by Use Case and Location, Hawaii

	Arbitrage	Regulation Reserve	Capacity	Fast Frequency Response	Total
Benefit	$7,441,760	$8,498,871	$25,347,134	$20,924	$41,308,689
Share of Total	18.0%	20.6%	61.4%	0.1%	

Results segmented by each cost case are presented in Table 3.14 and Figure 3.13.

Table 3.14. Co-Optimized Present Value Benefits and Costs Stratified by Cost Method, Hawaii

	Base	Low Cost Method	High Cost Method	Mature Cost Method
Benefits	$41,308,689	$41,308,689	$41,308,689	$41,308,689
Costs	$35,527,618	$25,910,071	$45,474,915	$26,447,196
Benefit-Cost Ratio	1.16	1.59	0.91	1.56

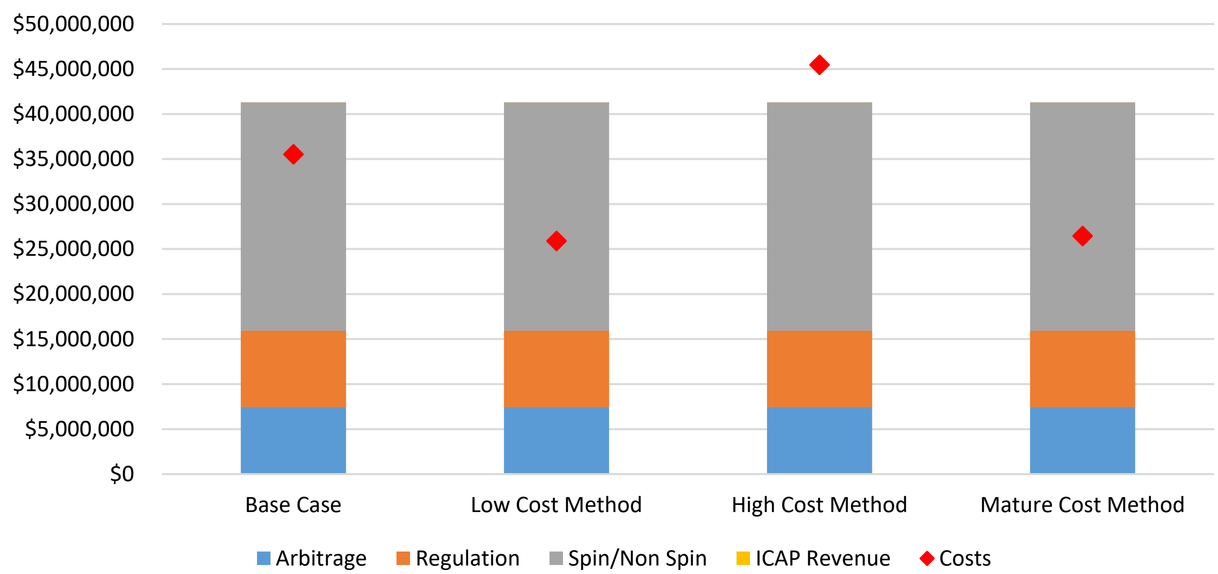


Figure 3.13. 30-Year Individual Present Value Benefits versus Costs by Cost Method, Hawaii

3.4.2 Evaluation of Alternative Scenarios and Sensitivity Analysis

To explore the sensitivity of the results to varying a number of key assumptions, the research team conducted a series of sensitivity analyses. The various scenarios are outlined below and their impacts were measured in comparison to the base case. Sensitivity analysis was performed by making the following adjustments to the assumptions:

- SA 1: Low Cost Method
- SA 2: High Cost Method
- SA 3: Mature Cost Method
- SA 4: +/- 1% Discount Rate

The results of each sensitivity analysis are presented in Figure 3.14. As shown, the low-cost and mature-cost scenarios result in positive changes in relation to the base case, while the high-cost method has a negative impact. Note that the increase and decrease in discount rate impacts the ROI ratio negatively and positively, respectively.

Table 3.15 presents the ROI ratios for the various scenarios as part of the sensitivity analysis. When the low-cost and mature-cost estimates presented by SENA are used in the denominator of the ROI calculations, both yield ROI ratios in excess of 1.0.

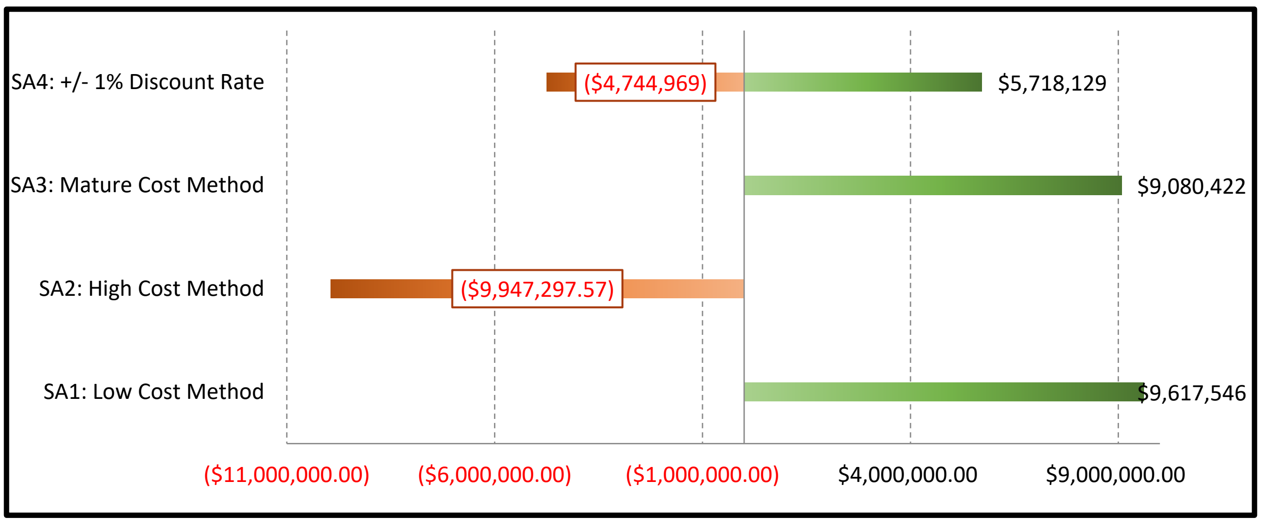


Figure 3.14. Sensitivity Analysis Results, Hawaii

Table 3.15. Benefit-Cost Ratios for Alternative Sensitivity Analysis Scenarios, Hawaii

Base Case	Low Cost	High Cost	Mature Cost	-1% Discount Rate	+1% Discount Rate
1.16	1.59	0.91	1.56	1.32	1.03

4.0 Conclusions

This assessment examined the financial feasibility of the SENA Hydro Battery by monetizing the values derived from seven services it could provide in four U.S. regions – the Pacific Northwest, CAISO service area, NYISO service area, and Hawaii. The hydro battery and the grid conditions in which it operates were modeled and an optimization tool was employed to explore tradeoffs between services and to develop optimal control strategies.

The results provide crucial insights into the practical application of the SENA Hydro Battery. The following lessons were drawn from this analysis.

1. The costs presented by SENA for the hydro battery are roughly comparable to those present in the marketplace for electrochemical battery systems of a similar scale. The all-in capital costs, inclusive of licensing but excluding debt-related costs, are estimated by SENA at $743/kWh. While li-ion costs for direct current (DC) modules and battery management systems have fallen to below $400/kWh in some cases, additional power conversion system, construction and commissioning, power control system, and electrical balance of plant costs result in all-in capital costs that are comparable to the hydro battery on a cost-per-kWh basis (Lahiri 2017).
2. Several hydro battery characteristics outlined by SENA are of tremendous value to the electrical grid. The ability to act as load and generation, the ability to follow a regulation signal, an ability to provide 14 MW of regulation up/down capacity, and the spinning reserve mode enabling grid synching improve project economics.
3. The highest return on investment ratio is provided by the Pearl Hill reference configuration, which represents the Pacific Northwest analysis. This location has a benefit cost ratio of 1.36 with $39.6 million in present value benefits compared to $29.0 million in costs. Hawaii provides the second highest ROI ratio (1.16) under the base case with over $41 million in 30-year present value benefits. Within the NYISO analysis, only two zones offered a positive ROI under the base case scenario – Hudson Valley (1.08 BCR) and Millwood (1.08 BCR). No other sub-region within the NYISO region and none of the sub-regions examined in the CAISO area offer ROIs greater than 1.0.
4. The most valuable services in any of the regions analyzed are capacity/RA and regulation. For the Pacific Northwest, capacity offers $11.4 million in 30-year PV benefits, closely followed by regulation up ($10.6 million). The CAISO analysis shows that within each of the five regions explored, regulation offers the highest benefit at $14.98 million. Within NYISO, the ICAP market provides the highest benefit for each sub-region at an average of $15.4 million, followed by regulation ($9.8 million). Capacity provides the highest benefit within the Hawaii hydro battery analysis as well at $25.3 million in present value benefits.
5. Sensitivity analysis shows positive returns on investment in both low-cost and mature-cost methods across each region. The low-end cost scenario covers the lower end of the ranges of uncertainty around plant and membrane capital costs (minus 30 percent and 50 percent, respectively). Under this scenario, all locations within all regions show a positive ROI ratio except for the SCE region within the CAISO analysis, which returns a ratio of 0.90. The mature system cost scenario, which incorporates learning from licensing and building the first SENA Hydro Battery, includes 30 percent lower capital costs and only $1 million for licensing costs. This scenario shows identical results as the low-cost scenario with all locations returning a positive ROI ratio except SCE, which produces a ratio of 0.88.

This report represents the output of all four market assessments for the SENA Hydro Battery –the Pacific Northwest, California, New York, and Hawaii. It represents the final Phase 1 deliverable under this research effort. In Phase 2, PNNL will update results based on cost and performance data collected by other team members throughout the study. Phase 2, which now also includes an economic assessment of the SENA Hydro Battery in Puerto Rico, will be completed in 2019.

5.0 References

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Appendix A

Energy Storage Value Taxonomy

Appendix A

Energy Storage Value Taxonomy

Table A.1. Energy Storage Value Taxonomy

Category	Service	Value
Bulk Energy	Capacity or Resource Adequacy	The ESS is dispatched during peak demand events to supply energy and shave peak energy demand. The ESS 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 ESS operator responds to an area control error (ACE) 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 ESS 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 energy storage system 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 California ISO (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.
Transmission Services	Transmission Congestion Relief	Use of an ESS to store energy when the transmission system is uncongested and provide relief during hours of high congestion.
	Transmission Upgrade Deferral	Use of an ESS 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.

Category	Service	Value
Distribution Services	Distribution Upgrade Deferral	Use of an ESS to reduce loading on a specific portion of the distribution system, thus delaying 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 alternating current (AC) electric power transmission and distribution system. VAR control manages the reactive power, usually attempting to get a power factor near unity.
	Conservation Voltage Reduction	Use of an ESS to reduce energy consumption by reducing feeder voltage.
Customer Services	Power Reliability	Power reliability refers to the use of an ESS to reduce or eliminate power outages to customers.
	Time of Use (TOU) 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 ESS to reduce the maximum power draw by electric load in order to avoid peak demand charges.

Source: Modified from Akhil et al. 2015.

Appendix B

Supplemental Data Tables

Appendix B

Supplemental Data Tables

Table B.1. Pacific Northwest Benefits Estimates by Use Case for Base Scenario, Base Mid-C Scenario, No Primary Frequency Response Scenario, and RTE Down 10 Percentage Points Scenario

Use Cases	Base Case	Base Mid-C	No Energy Reserve for Primary Frequency Response	RTE Down 10 Percentage Points (57.262%)
Charging Costs	$(5,890,984)	$(4,993,826)	$(5,902,522)	$(5,182,145)
Discharging	$8,009,055	$4,244,510	$8,021,281	$6,546,790
Regulation Up	$10,609,706	$10,570,697	$10,643,202	$11,067,188
Regulation Down	$7,645,412	$7,975,232	$7,635,876	$7,487,405
Spin Reserve	$2,061,796	$1,815,119	$2,041,539	$1,980,085
Non-Spin Reserve	$832,526	$744,823	$840,244	$696,465
Primary Frequency Response	$4,935,299	$4,935,299	$4,935,299	$4,935,299
Capacity	$11,389,150	$11,389,150	$11,389,150	$11,389,150
Total Value	**$39,591,959**	**$36,681,006**	**$39,920,236**	**$38,920,235**

Table B.2. Pacific Northwest Benefits Estimates by RTE Up 10 Percentage Points Scenario, 20MWh of Capacity Scenario, 40MWh of Capacity Scenario, and No PFR to Actually No PFR Scenario

Use Cases	RTE Up 10 Percentage Points (77.262%)	20MWh of Capacity	40MWh of Capacity	Primary Frequency Response Excluded
Charging Costs	$(6,699,963)	$(5,340,627)	$(6,234,648)	$(5,890,984)
Discharging	$9,636,782	$7,242,599	$8,572,627	$8,009,055
Regulation Up	$10,019,563	$10,394,933	$10,024,642	$10,609,706
Regulation Down	$7,944,476	$7,818,099	$8,077,125	$7,645,412
Spin Reserve	$2,227,168	$1,679,981	$2,451,290	$2,061,796
Non-Spin Reserve	$832,290	$635,066	$896,105	$832,526
Primary Frequency Response	$4,935,299	$4,935,299	$4,935,299	
Capacity	$11,389,150	$11,389,150	$11,389,150	$11,389,150
Total Value	**$40,284,766**	**$38,754,500**	**$40,111,590**	**$34,656,661**

Table B.3. Pacific Northwest Benefits Estimate by Use Case for 2014 Mid-C Prices and 2015 EIM Prices

Use Cases	2014 Mid-C Prices	2015 EIM Prices
Charging Costs	$(7,392,403)	$(5,950,118)
Discharging	$7,807,701	$7,293,627
Regulation Up	$10,606,058	$10,259,799
Regulation Down	$7,678,113	$8,085,725
Spin Reserve	$1,325,555	$1,609,247
Non-Spin Reserve	$553,979	$724,958
Primary Frequency Response	$4,935,299	$4,935,299
Capacity	$11,389,150	$11,389,150
Total Value	**$36,903,452**	**$38,347,686**

Table B.4. Pacific Northwest Benefits Estimates by Use Case for PGE Values for Flexibility and PSE Values for Flexibility Scenarios

Use Cases	PGE Values for Flexibility	PSE Values for Flexibility
Flexibility	$7,972,405	$19,133,773
Primary Frequency Response	$4,935,299	$4,935,299
Capacity	$11,389,150	$11,389,150
Total Value	**$24,296,854**	**$35,458,222**

Table B.5. Co-Optimized 30 Year Benefits by Use Case for Each CAISO Location

Area	Service	Co-Optimized 30 Year Benefits
PG&E	Arbitrage	$3,853,192
	Regulation	$15,292,767
	Spin/Non-Spin	$883,236
	RA Capacity	$750,973
	Primary Frequency Response	$5,637,747
	Total	**$26,417,914**
SCE	Arbitrage	$3,318,777
	Regulation	$12,379,687
	Spin/Non-Spin	$711,964
	RA Capacity	$528,284
	Primary Frequency Response	$4,587,350
	Total	**$21,526,062**
SDG&E	Arbitrage	$4,423,997
	Regulation	$16,372,998
	Spin/Non-Spin	$1,175,357
	RA Capacity	$649,785
	Primary Frequency Response	$6,078,547
	Total	**$28,700,683**

Area	Service	Co-Optimized 30 Year Benefits
Folsom	Arbitrage	$4,020,904
	Regulation	$15,180,235
	Spin/Non-Spin	$973,917
	RA Capacity	$755,309
	Primary Frequency Response	$5,637,747
	Total	**$26,568,112**
Ramona	Arbitrage	$6,287,935
	Regulation	$15,684,703
	Spin/Non-Spin	$1,077,124
	RA Capacity	$601,444
	Primary Frequency Response	$6,078,547
	Total	**$29,729,753**

Table B.6. CAISO Annual Values by Use Case by Location for the Base Case

	PG&E	SCE	SDG&E	Folsom	Ramona
Arbitrage	$180,434	$190,994	$192,141	$188,288	$273,094
Regulation	$716,118	$712,446	$711,103	$710,848	$681,209
Spin/Non-Spin	$41,359	$40,973	$51,047	$45,606	$46,781
RA Capacity	$35,166	$30,403	$28,221	$35,369	$26,122
Frequency Response	$264,000	$264,000	$264,000	$264,000	$264,000
Total	**$1,237,077**	**$1,238,815**	**$1,246,512**	**$1,244,111**	**$1,291,206**

Table B.7. CAISO 30-Year PV Benefits – PV Costs by Sensitivity Analysis Scenario and Location

	No Primary Frequency Response	Forecast Values Used	+1% Discount Rate	-1% Discount Rate	Low Cost Method
PG&E	$ (10,627,230)	$ (5,335,481)	$ (8,013,019)	$ (4,217,146)	$2,535,588
SCE	$ (14,701,556)	$ (6,584,630)	$ (12,068,321)	$ (10,160,669)	$ (2,356,265)
SDG&E	$ (9,096,501)	$ (4,812,347)	$ (6,417,325)	$ (1,764,879)	$4,593,052
Folsom	$ (10,871,499)	$ (6,786,560)	$ (8,175,527)	$ (4,370,701)	$2,460,480
Ramona	$ (8,927,852)	$ (4,002,665)	$ (5,518,215)	$ (577,022)	$5,622,121
	High Cost Method	**Mature Cost Method**	**$0.50 RA Price**	**$5 RA Price**	**$12.50 RA Price**
PG&E	$ (15,498,094)	$2,040,499	$ (6,826,979)	$ (5,151,613)	$ (2,110,446)
SCE	$ (20,389,947)	$ (2,851,354)	$ (11,494,589)	$ (10,304,375)	$ (7,853,247)
SDG&E	$ (13,610,759)	$4,093,292	$ (4,664,227)	$ (3,188,553)	$56,713
Folsom	$ (15,743,331)	$1,960,721	$ (6,984,742)	$ (5,306,062)	$ (2,263,305)
Ramona	$ (12,581,690)	$5,122,362	$ (3,591,072)	$ (2,213,029)	$986,469

Table B.8. 30-Year NYISO Present Values by Use Case by Location

Area	Service	Co-Optimized 30 Year Benefits
Capital	Arbitrage	-$270,565
	Regulation	$10,069,166
	Spin/Non-Spin	$4,513,417
	ICAP Revenue	$12,474,256
	Total	**$26,786,273**
Central	Arbitrage	$681,404
	Regulation	$10,001,072
	Spin/Non-Spin	$4,112,242
	ICAP Revenue	$12,474,256
	Total	**$27,268,973**
Dunwood	Arbitrage	$347,626
	Regulation	$10,043,796
	Spin/Non-Spin	$4,459,831
	ICAP Revenue	$18,881,525
	Total	**$33,732,778**
Genesee	Arbitrage	$595,297
	Regulation	$10,041,628
	Spin/Non-Spin	$4,120,729
	ICAP Revenue	$12,474,256
	Total	**$27,231,909**
Hudson Valley	Arbitrage	$194,922
	Regulation	$10,034,635
	Spin/Non-Spin	$4,475,770
	ICAP Revenue	$18,881,525
	Total	**$33,586,851**
Long Island	Arbitrage	$1,281,760
	Regulation	$9,770,755
	Spin/Non-Spin	$4,413,876
	ICAP Revenue	$14,852,083
	Total	**$30,318,474**
Mohawk Valley	Arbitrage	$600,180
	Regulation	$9,974,583
	Spin/Non-Spin	$4,130,117
	ICAP Revenue	$12,474,256
	Total	**$27,179,136**
Millwood	Arbitrage	$241,383
	Regulation	$10,053,108
	Spin/Non-Spin	$4,485,152
	ICAP Revenue	$18,881,525
	Total	**$33,661,168**
North	Arbitrage	$468,203
	Regulation	$9,940,321
	Spin/Non-Spin	$4,192,033
	ICAP Revenue	$12,474,256
	Total	**$27,074,813**

Area	Service	Co-Optimized 30 Year Benefits
NYC	Arbitrage	$396,496
	Regulation	$8,129,821
	Spin/Non-Spin	$3,615,590
	ICAP Revenue	$20,175,909
	Total	**$32,317,816**

Table B.9. Annual NYISO Values by Use Case by Location for the Base Case

	Capital	Central	Dunwood	Genesee	Hudson Valley
Arbitrage	-$13,100	$32,991	$16,831	$28,822	$9,438
Regulation	$487,518	$484,221	$486,290	$486,185	$485,846
Spin/Non-Spin	$218,526	$199,102	$215,931	$199,513	$216,703
RA Capacity	$603,966	$603,966	$914,186	$603,966	$914,186
Total	**$1,296,910**	**$1,320,281**	**$1,633,238**	**$1,318,486**	**$1,626,173**
	Long Island	**Mohawk Valley**	**Millwood**	**North**	**NYC**
Arbitrage	$62,059	$29,059	$11,687	$22,669	$23,489
Regulation	$473,070	$482,939	$486,741	$481,280	$481,632
Spin/Non-Spin	$213,706	$199,968	$217,157	$202,965	$214,197
RA Capacity	$719,093	$603,966	$914,186	$603,966	$1,195,273
Total	**$1,467,928**	**$1,315,931**	**$1,629,771**	**$1,310,880**	**$1,914,591**

Table B.10. 30-Year NYISO PV Benefits – PV Costs by Sensitivity Analysis Scenario and Location

	+1% Discount Rate	-1% Discount Rate	Low Cost Method	High Cost Method	Mature Cost Method
Capital	-$6,170,675	-$2,228,171	$4,030,472	-$13,152,565	$3,558,736
Central	-$6,040,504	-$2,000,890	$4,287,866	-$13,065,299	$3,811,460
Dunwood	-$5,653,973	-$460,464	$6,696,181	-$13,719,308	$6,135,704
Genesee	-$6,956,092	-$3,021,723	$3,574,888	-$14,288,665	$3,084,469
Hudson Valley	-$190,015	$5,568,394	$10,831,049	-$6,351,987	$10,359,314
Long Island	-$6,890,641	-$2,418,132	$4,633,708	-$14,761,007	$4,101,254
Mohawk Valley	-$5,825,179	-$1,777,771	$4,423,334	-$12,759,703	$3,951,598
Millwood	-$124,658	$5,653,595	$10,905,367	-$6,277,670	$10,433,631
North	-$5,033,930	-$919,032	$4,994,926	-$11,677,723	$4,537,203
NYC	-$6,547,048	-$2,558,652	$5,281,219	-$15,134,269	$4,720,742

	Top 5% Loading	Top 10% Loading	Top 20% Loading	Forecast Values Used
Capital	-$3,430,074	-$3,580,003	-$3,842,792	-$4,558,959
Central	-$3,534,586	-$3,629,589	-$3,783,916	-$4,474,868
Dunwood	-$2,348,567	-$2,458,210	-$2,747,816	-$3,534,771
Genesee	-$4,453,105	-$4,549,258	-$4,689,308	-$5,426,533

	Top 5% Loading	Top 10% Loading	Top 20% Loading	Forecast Values Used
Hudson Valley	$3,399,604	$3,197,400	$2,926,677	$2,215,332
Long Island	-$3,933,717	-$4,015,288	-$4,289,952	-$5,206,456
Mohawk Valley	-$3,270,841	-$3,350,291	-$3,492,426	-$4,189,484
Millwood	$3,362,798	$3,226,335	$3,044,071	$2,242,578
North	-$2,136,868	-$2,235,557	-$2,412,844	-$3,471,296
NYC	-$3,928,191	-$3,967,493	-$4,168,000	-$4,934,187

Table B.11. Annual NYISO Total Hours of Battery Activity by Application and Location

	Capital	Central	Dunwood	Genesee	Hudson Valley
Generation	1,505	1,558	1,504	1,559	1,498
Pump	6,231	6,068	6,092	6,140	6,157
Generation & Pump	5	26	7	36	11
Regulation	7,210	7,102	7,156	7,120	7,175
Spin	4,819	4,453	4,774	4,561	4,841
Non-Spin	1,401	1,391	1,475	1,387	1,467
Supplemental	1,078	1,437	1,047	1,335	989
ICAP	1,460	1,460	1,460	1,460	1,460
	Long Island	**Mohawk Valley**	**Millwood**	**North**	**NYC**
Generation	1,540	1,554	1,499	1,699	1,499
Pump	5,590	6,018	6,104	6,086	5,842
Generation & Pump	0	25	5	92	0
Regulation	7,016	7,086	7,165	7,050	7,090
Spin	4,789	4,460	4,771	4,446	4,843
Non-Spin	1,449	1,419	1,439	1,402	1,409
Supplemental	1,050	1,401	1,088	1,404	1,046
ICAP	1,460	1,460	1,460	1,460	1,460

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