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Hydropower and High Capacity Energy Storage

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Water Power Technologies Office

U.S. DEPARTMENT OF ENERGY BATTELLE HydroWIRES U.S. DEPARTMENT OF ENERGY

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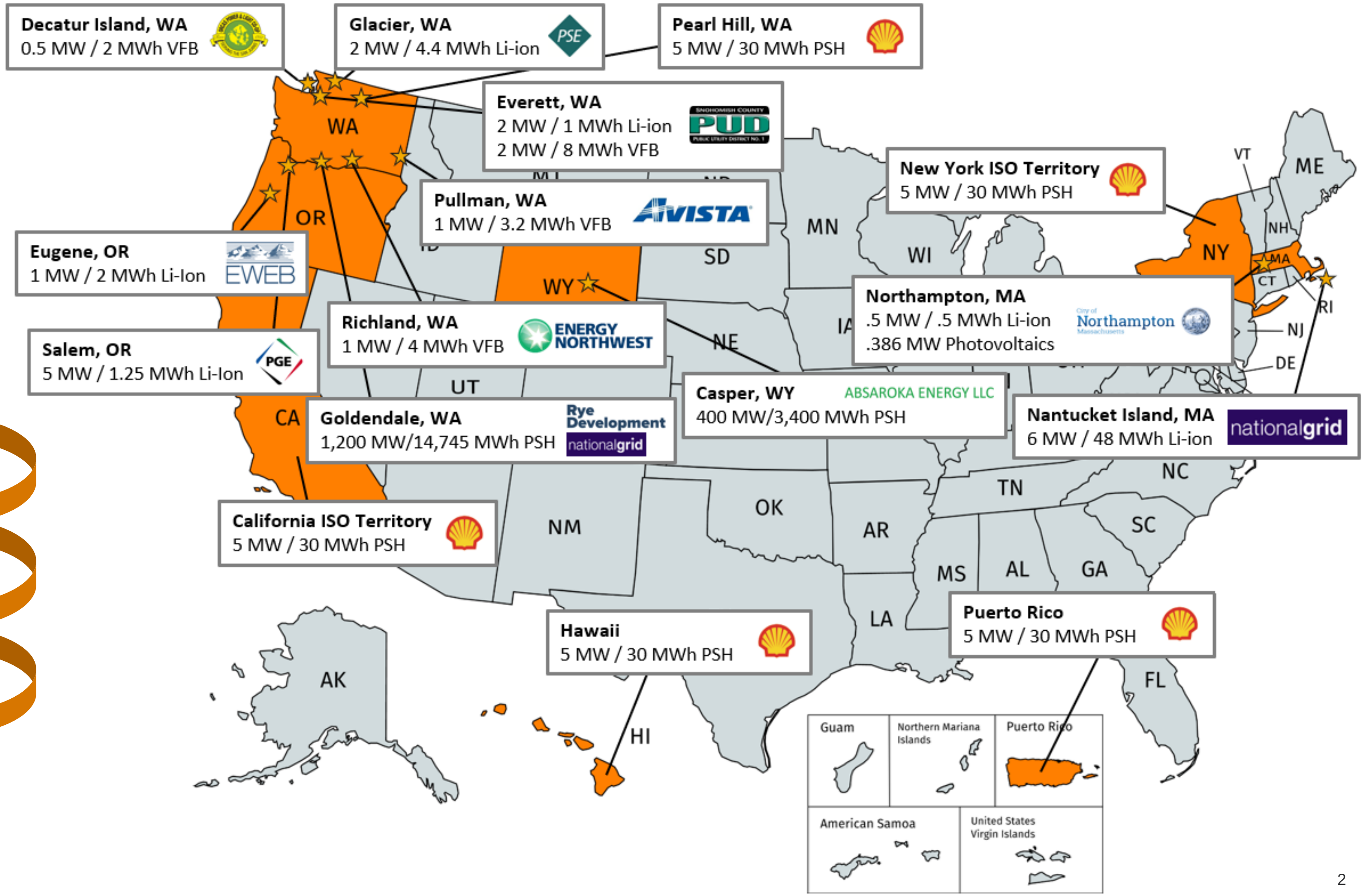
Energy Storage Techno-Economic Assessments at Pacific Northwest National Laboratory

PNNL Storage Analytics Program

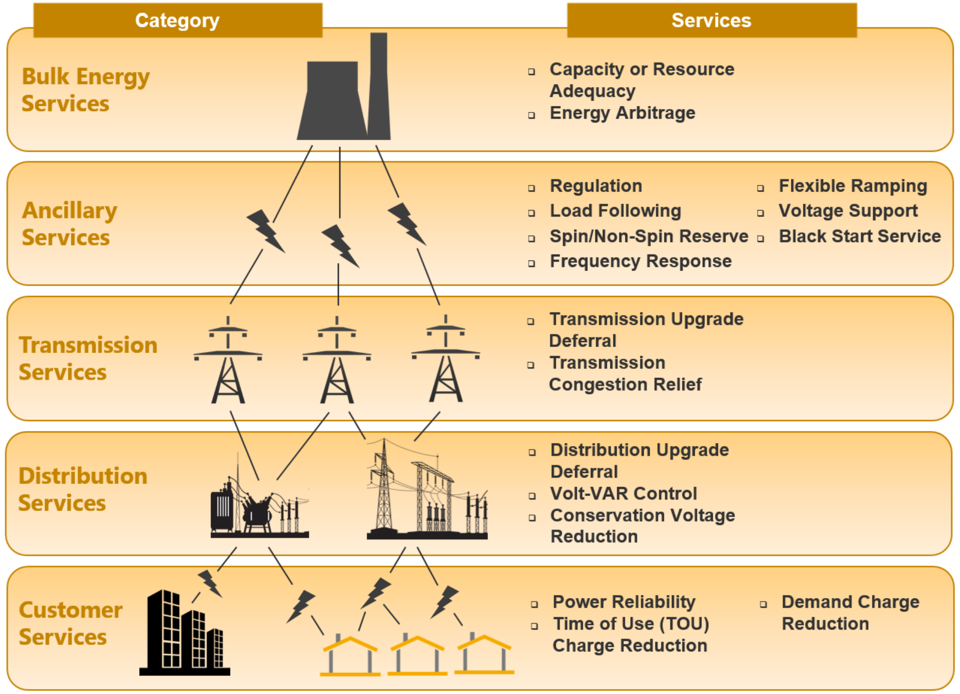
1,626 MW 18,248 MWh at 16 Sites

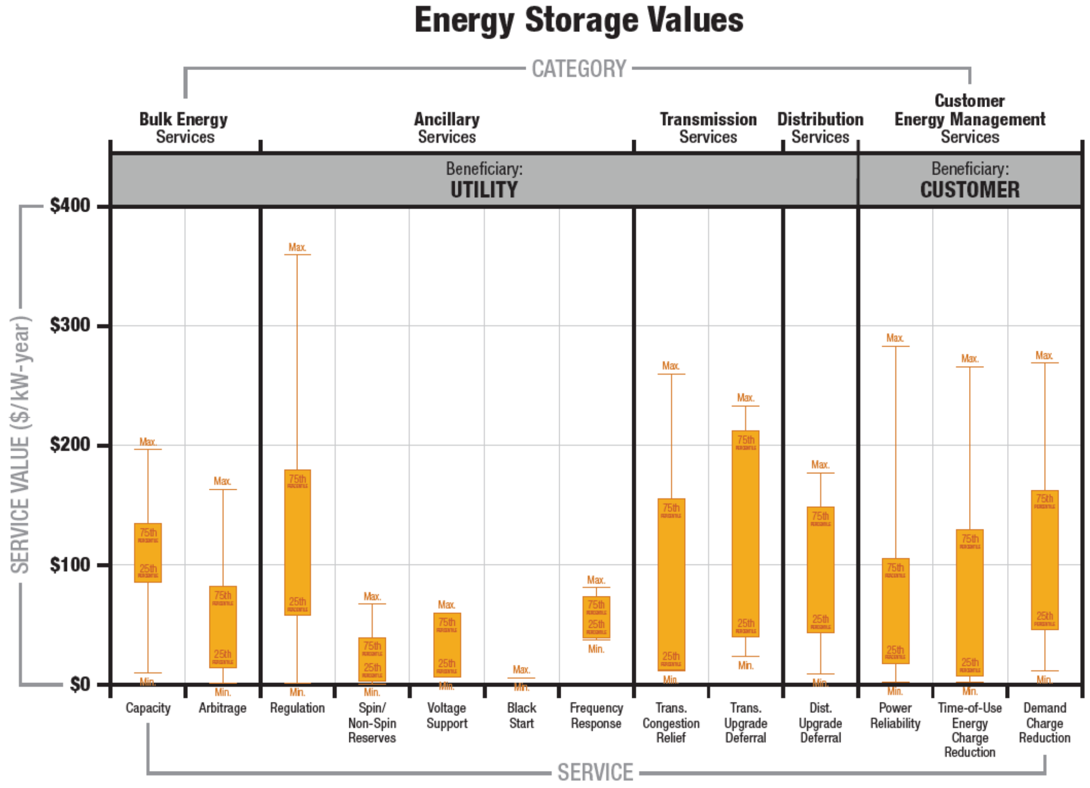
PNNL Analytics Task-flow

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



Defining and Monetizing the Value of Energy Storage and Distributed Energy Resources (DERs) More Broadly



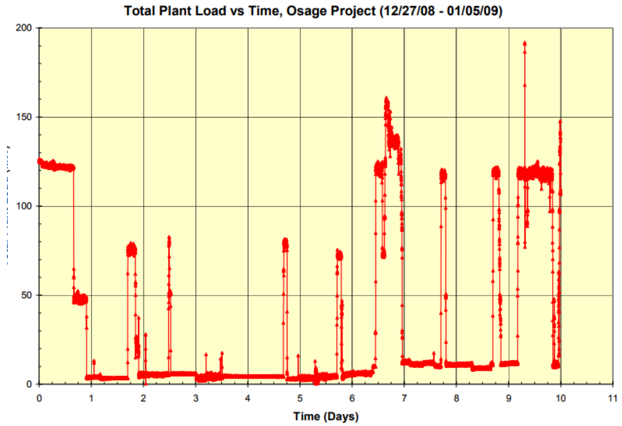


Key takeaways:

- We have developed a broad taxonomy and modeling approach for defining the value of DERs
- Economic value is highly dependent on siting and scaling of energy storage resources; many benefits accrue directly to customers
- Benefits differ based on utility structure (e.g., public utility districts (PUDs), co-ops, vertically integrated utilities) and market operation
- Accurate characterization of Battery Energy Storage System (BESS) performance, and development of real-time control strategies, are essential to maximizing value to the electrical grid

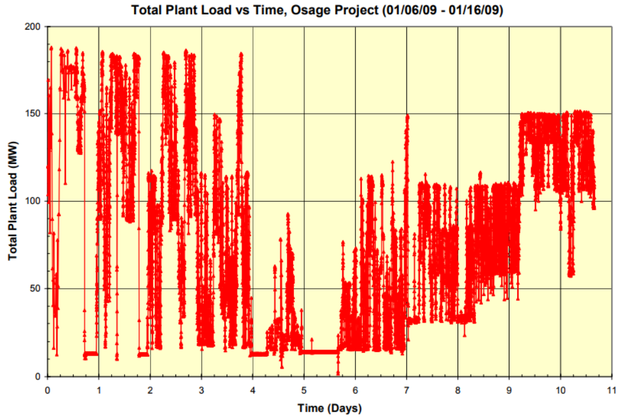
Hydropower and Pumped Storage Hydro (PSH) are Changing Rapidly

Traditional Hydro: from steady or predictable patterns to fast and frequent ramping



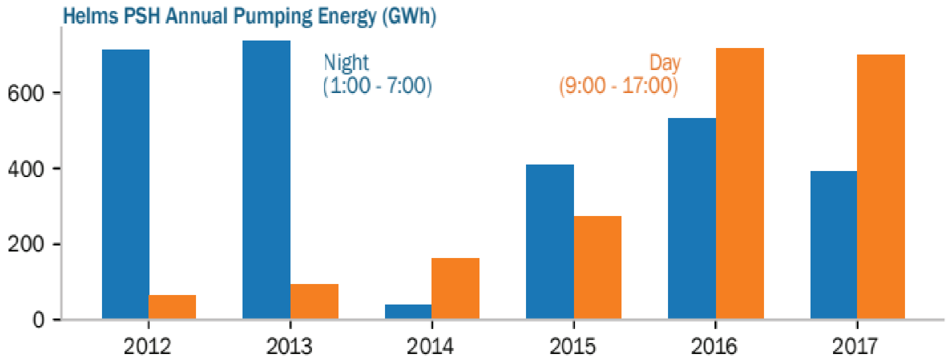
Weekly generation:
(Osage Power Plant, MO)

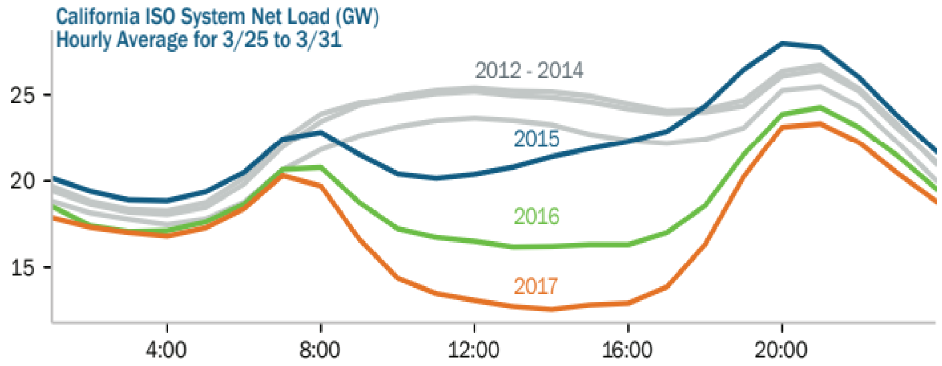
Before participation in ancillary services market



After participation in ancillary services market

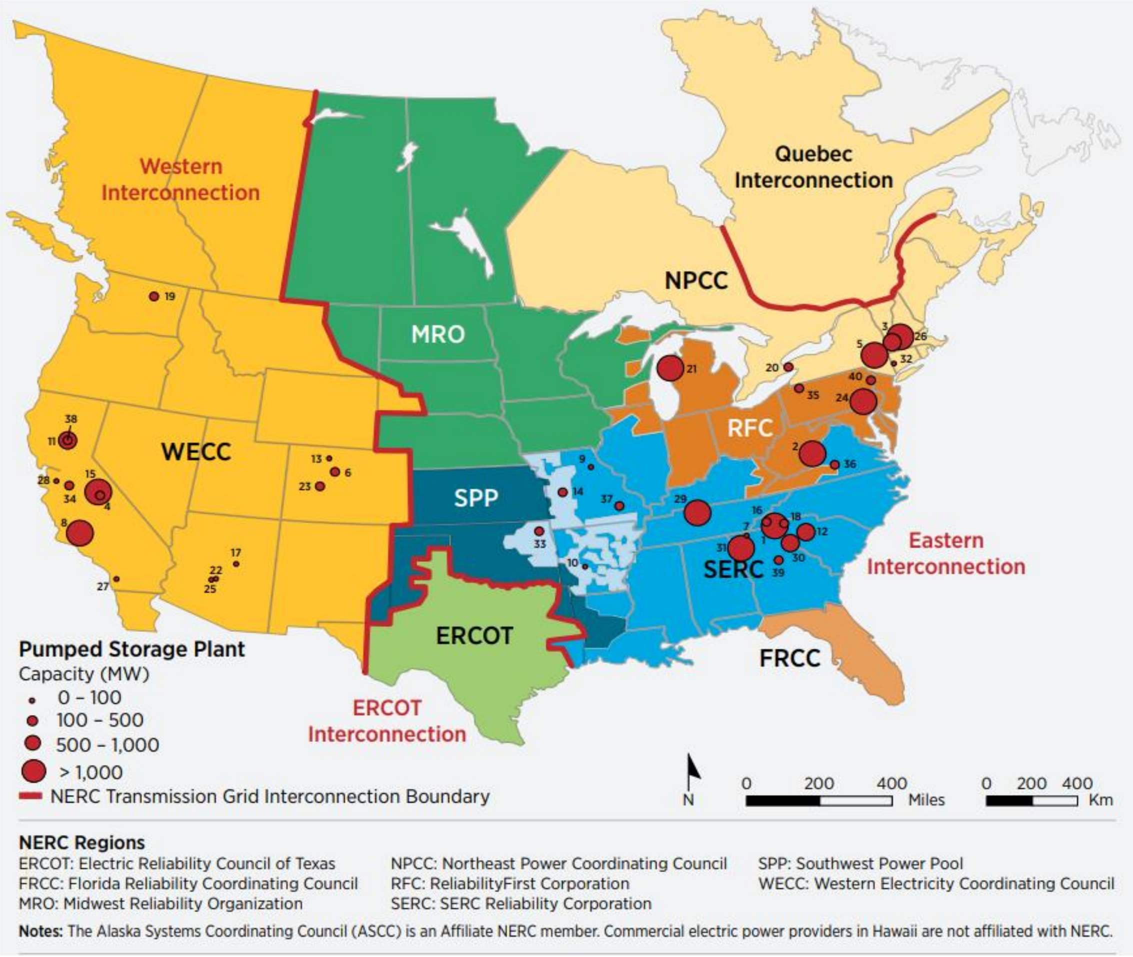
Pumped Storage: from day/night arbitrage to fast response

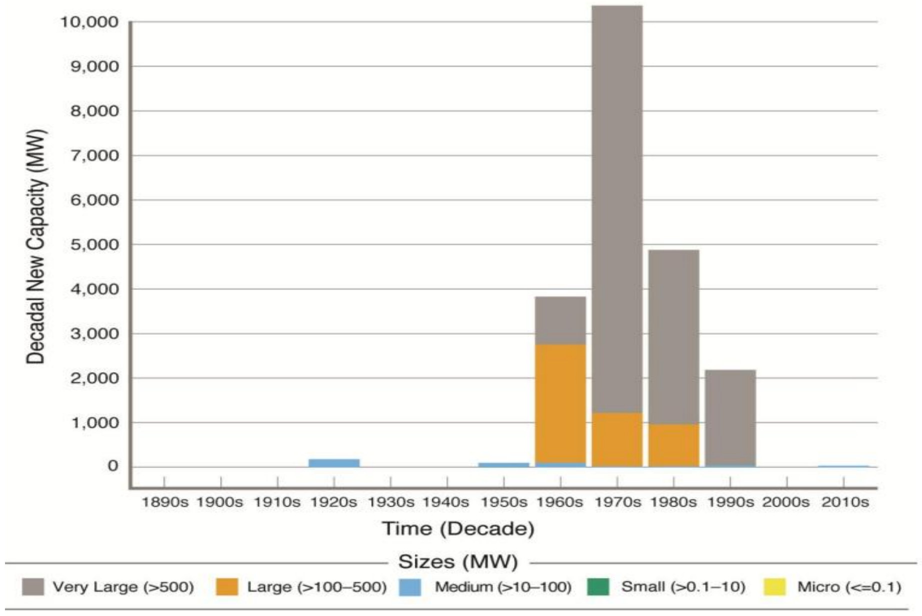




Annual Pumping Energy Consumption by Helms PSH vs. CAISO Net Load in the Last Week of March

PSH in the U.S.





Note: This figure displays the initial year of operation for each project except in two cases (Hiwassee and Grand Coulee) in which no pumped storage units were installed when they first became operational. In those two cases, the capacity was assigned to the decade in which the pumped storage units were added.

Source: NHAAP

Figure 18. Pumped storage hydropower installation timeline by plant size

About 22 GW of PSH capacity deployed in the US, but no new large projects in the last 20 years

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HydroWIRES Initiative

- Given the rapid changes occurring in the U.S. electric system—and associated challenges and opportunities—the Water Power Technologies Office (WPTO) has launched a new hydropower-grid research initiative titled **HydroWIRES: Water Innovation for a Resilient Electricity System.**
- The mission of HydroWIRES is <u>to understand, enable, and improve hydropower's contributions to reliability, resilience, and integration</u> in a rapidly evolving electricity system.

HydroWIRES
U.S. DEPARTMENT OF ENERGY

https://energy.gov/HydroWIRES

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HydroWIRES Program Areas

HydroWIRES U.S. DEPARTMENT OF ENERGY

Value under Evolving System Conditions

Understand the needs of the rapidly evolving grid and how they create opportunities for hydropower and PSH.

“What will the grid need?”

Capabilities and Constraints

Investigate the full range of hydropower’s capabilities to provide grid services, as well as the machine, hydrologic, and institutional constraints to fully utilizing those capabilities.

What can hydropower do?”

Operations and Planning

Optimize hydropower operations and planning—alongside other resources—to best utilize hydropower’s capabilities to provide grid services.

“How can hydropower best align what it can do with what the grid will need?”

Technology Innovation

Invest in innovative technologies that improve hydropower capabilities to provide grid services.

“What new technology could expand what hydropower can do to meet grid needs?”

Pumped Storage Hydro Techno-Economic Studies

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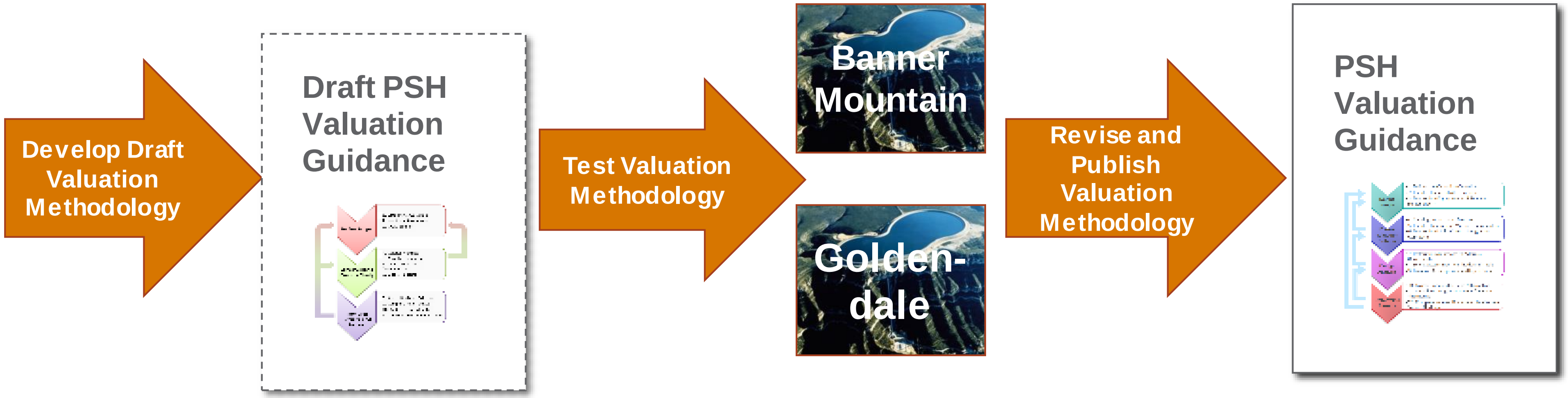
HydroWIRES U.S. DEPARTMENT OF ENERGY

Objective: Advance the state of the art in the assessment of value of PSH plants and their role and contributions to the power system

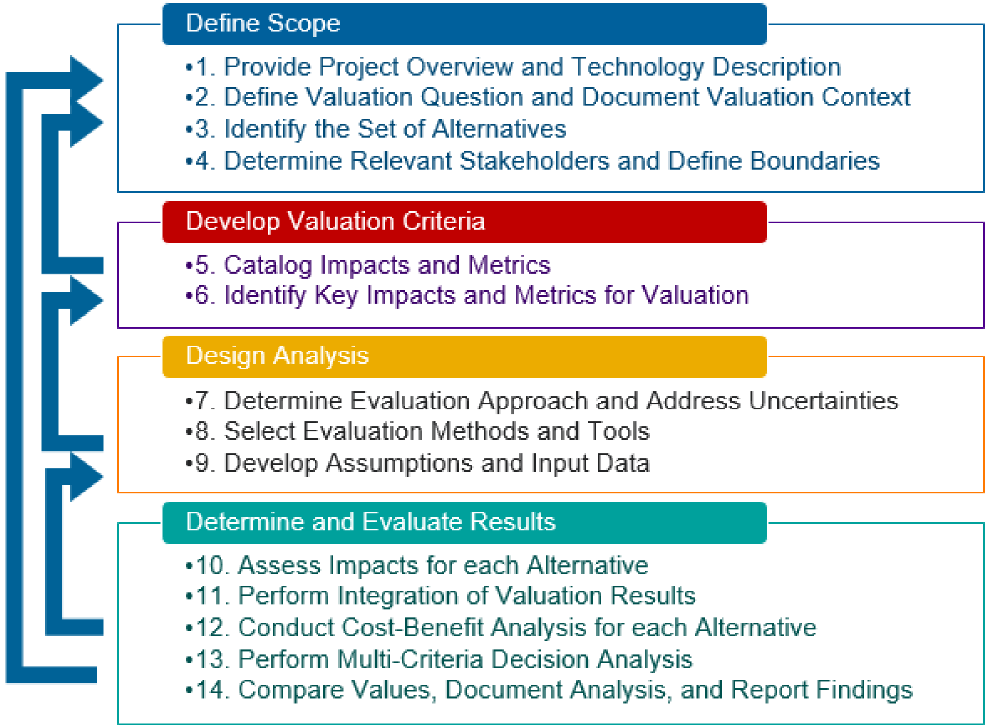
Specific goals:

1. Develop a comprehensive and transparent valuation guidance that will allow for consistent valuation assessments and comparisons of PSH projects
2. Test the PSH valuation methodology by applying it to two selected PSH projects
3. Transfer and disseminate the PSH valuation guidance to the hydropower industry, PSH developers, and other stakeholders



Approach and Use Case Coverage – PSH Techno-economic Studies

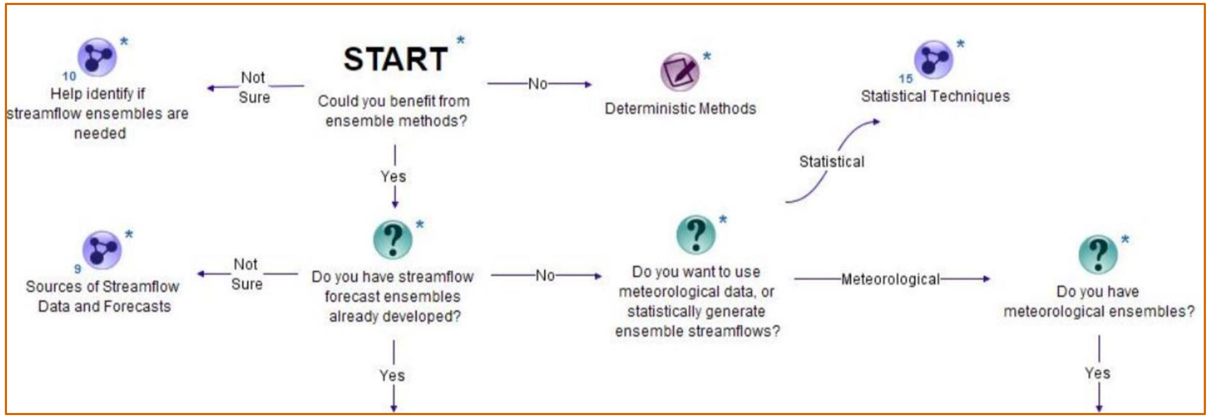
- Bulk power capacity and energy value over PSH lifetime
- Value of PSH ancillary services (regulation service, contingency reserves, etc.)
- Power system stability services (inertial response, governor response, transient and small signal stability, voltage support)
- PSH impacts on reducing system cycling and ramping costs
- Other indirect (system-wide or portfolio) effects of PSH operations (e.g., PSH impacts on decreasing overall power system production costs, benefits for integration of variable energy resources, and impacts on emissions)

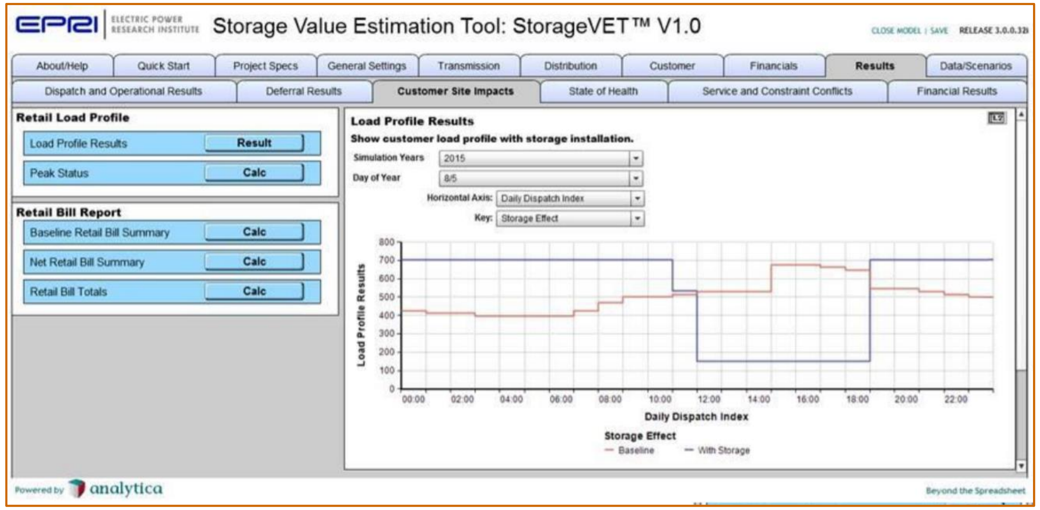


Cost-Benefit and Decision Analysis Framework

- PSH transmission benefits (transmission congestion relief, transmission investments deferral)
- PSH non-energy services (water management services, socioeconomic benefits, and environmental impacts)

Pumped Storage Hydro Tool





Decision Tree Model

Comprehensive Model

Key takeaways:

- We thought a tool would be more effective than a document to users when conducting project assessments
- The two basic structures we propose are a decision-tree-based model and a comprehensive tool
- When building a tool, decisions about its basic structure are dictated by user, budget, and technical feasibility considerations
- Our preliminary approach is to design a decision-tree-based model with an embedded price-taker model and an off-ramp for guiding the user when using a price-maker model.

Objectives of Energy Storage Cost and Performance Characterization Study

Objectives: To define and compare energy storage technology costs and to evaluate these technologies across a variety of performance parameters

- Cost and performance characteristics are presented for the following energy storage technologies:
  - Lithium-ion batteries
  - Lead-acid batteries
  - Redox flow batteries
  - Sodium-sulfur batteries
  - Sodium metal halide batteries
  - Zinc-hybrid cathode batteries
  - Pumped storage hydropower
  - Flywheels
  - Compressed air energy storage
  - Ultracapacitors
- Cost information procured for most recent year for which data are available; data procured from literature and industry survey/contacts/data
- Base year used is 2018 and projections for 2025 were developed.

Cost and Performance – Non-BESS Energy Storage Systems (cont)

Parameter	Pumped Storage Hydropower	Combustion Turbine	CAES	Flywheel	Ultracapacitor
Capital Cost – Energy Capacity ($/kW)	1,700-3,200 2,638	678-1,193 940	1,050-2,544 1,669	600-2,400 2,400	240-400 400
Power Conversion System (PCS) ($/kW)	Included in Capital Cost	N/A	N/A	Included in Capital Cost	350 (255)
Balance of Plant (BOP) ($/kW)					100 (95)
Construction and Commissioning ($/kW)				480	80
Total Project Cost ($/kW)	1,700-3,200 2,638	678-1,193 940	1,050-2,544 1,669	1,080-2,880 2,880	930 (835)
Total Project Cost ($/kWh)[a]	106-200 165		94-229 105	4,320-11,520 11,520	74,480 (66,640)
O&M Fixed ($/kW-year)	15.9	13.0	16.7	5.6	1
O&M Variable (cents/kWh)	0.00025	1.05	0.21	0.03	0.03
System Round-Trip Efficiency (RTE)	0.80	0.328	0.52	0.86	0.92
Annual RTE Degradation Factor				0.14%	0.14%
Cycles at 80% Depth of Discharge	15,000	Not Relevant	10,000	200,000	1 million
Life (Years)	>25	20	25	>20	16
MRL	9 (10)	10	8 (9)	8 (9)	9
TRL	8 (9)	9	7 (8)	7(8)	8

(a) Assumed energy to power ratios – CAES and PSH = 16, ultracapacitor = 0.125, and flywheel = .25.

Cost and Performance – Non-BESS Energy Storage Systems (cont)

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Power Conversion System (PCS) ($/kW)	Included in Capital Cost	N/A	N/A	Included in Capital Cost	350 (255)
Balance of Plant (BOP) ($/kW)					100 (95)
Construction and Commissioning ($/kW)			[illegible]	[illegible]	[illegible]
Total Project Cost ($/kW)	1,700-3,200 2,638	678-1,19 940	[illegible]	[illegible]	[illegible]
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MRL	9 (10)	10	8 (9)	8 (9)	9
TRL	8 (9)	9	7 (8)	7(8)	8

(a) Assumed energy to power ratios – CAES and PSH = 16, ultracapacitor = 0.125, and flywheel = .25.

PSH represents a mature, efficient, and cost-effective option when measured in terms of $ per kWh of stored energy.

Cost and Performance – Battery Energy Storage Systems

Parameter	Sodium-Sulfur Battery 2018	Sodium-Sulfur Battery 2025	Li-Ion Battery 2018	Li-Ion Battery 2025	Lead Acid 2018	Lead Acid 2025	Redox Flow Battery 2018	Redox Flow Battery 2025
Capital Cost – Energy Capacity ($/kWh)	400-1,000	(300-675)	223-323	(156-203)	120-291	(102-247)	435-952	(326-643)
	661	(465)	271	(189)	260	(220)	555	(393)
Power Conversion System (PCS) ($/kW)	230-470	(184-329)	230-470	(184-329)	230-470	(184-329)	230-470	(184-329)
	350	(211)	288	(211)	350	(211)	350	(211)
Balance of Plant (BOP) ($/kW)	80-120	(75-115)	80-120	(75-115)	80-120	(75-115)	80-120	(75-115)
	100	(95)	100	(95)	100	(95)	100	(95)
Construction and Commissioning ($/kWh)	121-145	(115-138)	92-110	(87-105)	160-192	(152-182)	173-207	(164-197)
	133	(127)	101	(96)	176	(167)	190	(180)
Total Project Cost ($/kW)	2,394-5,170	(1,919-3,696)	1,570-2,322	(1,231-1,676)	1,430-2,522	(1,275-2,160)	2,742-5,226	(2,219-3,804)
	3,626	(2,674)	1,876	(1,446)	2,194	(1,854)	3,430	(2,598)
Total Project Cost ($/kWh)	599-1,293	(480-924)	393-581	(308-419)	358-631	(319-540)	686-1,307	(555-951)
	907	(669)	469	(362)	549	(464)	858	(650)
O&M Fixed ($/kW-yr)	10	(8)	10	(8)	10	(8)	10	(8)
O&M Variable (cents/kWh)	0.03		0.03		0.03		0.03	
System Round-Trip Efficiency (RTE)	0.75		0.86		0.72		0.675	(0.7)
Annual RTE Degradation Factor	0.34%		0.50%		5.40%		0.40%	
Response Time (limited by PCS)	1 sec		1 sec		1 sec		1 sec	
Cycles at 80% Depth of Discharge	4,000		3,500		900		10,000	
Life (Years)	13.5		10		2.6	(3)	15	

(a) An E/P ratio of 4 hours was used for battery technologies when calculating total costs. Sodium metal halide and zinc-hybrid cathode not included on slide.

Cost and Performance – Battery Energy Storage Systems

Parameter	Sodium-Sulfur Battery 2018	Sodium-Sulfur Battery 2025	Li-Ion Battery 2018	Li-Ion Battery 2025	Lead Acid 2018	Lead Acid 2025	Redox Flow Battery 2018	Redox Flow Battery 2025
Capital Cost – Energy Capacity ($/kWh)	400-1,000	(300-675)	223-323	(156-203)	120-291	(102-247)	435-952	(326-643)
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	)	555	(393)
Power Conversion System (PCS) ($/kW)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	29)	230-470	(184-329)
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	)	350	(211)
Balance of Plant (BOP) ($/kW)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	5)	80-120	(75-115)
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	100	(95)
Construction and Commissioning ($/kWh)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	82)	173-207	(164-197)
	133	(127)	101	(96)	176	(167)	190	(180)
Total Project Cost ($/kW)	2,394-5,170	(1,919-3,696)	1,570-2,322	(1,231-1,676)	1,430-2,522	(1,275-2,160)	2,742-5,226	(2,219-3,804)
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O&M Fixed ($/kW-yr)	10	(8)	10	(8)	10	(8)	10	(8)
O&M Variable (cents/kWh)	0.03		0.03		0.03		0.03	
System Round-Trip Efficiency (RTE)	0.75		0.86		0.72		0.675	(0.7)
Annual RTE Degradation Factor	0.34%		0.50%		5.40%		0.40%	
Response Time (limited by PCS)	1 sec		[illegible]		[illegible]		[illegible]	
Cycles at 80% Depth of Discharge	[illegible]		[illegible]		[illegible]		[illegible]	
Life (Years)	[illegible]		[illegible]		[illegible]		[illegible]	

(a) An E/P ratio of 4 hours was used for b[illegible]

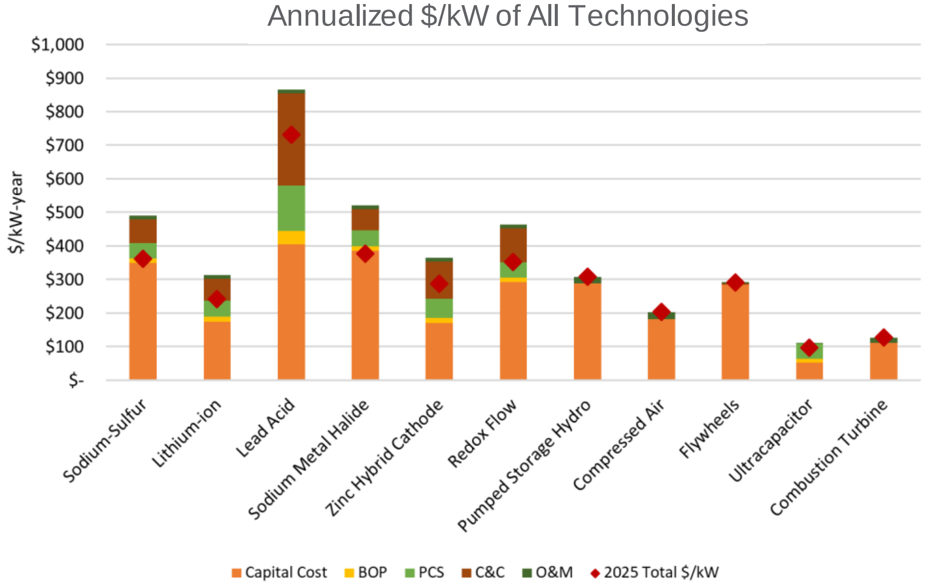
Capital costs are broken down by component – capital (DC modules and BMS), PCS, BOP and construction/commissioning. By component, costs are calculated based on either energy (kWh) or power (kW) capacities. We present range and point estimates.

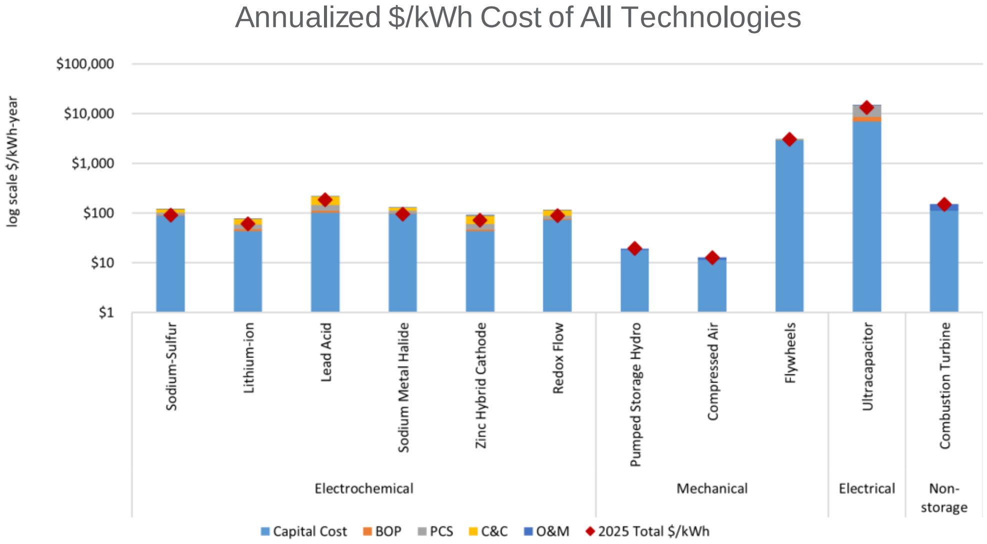
Total costs calculated for illustrative 1 MW / 4 MWh BESS. Li-Ion has lowest initial capital costs today.

We include several performance metrics.

Cost and Technical Performance Takeaways

- Among the battery systems, Li-ion offers the best option today in terms of cost, performance, calendar and cycle life, and technology maturity
- For longer-term storage, PSH and compressed air energy storage (CAES) give the lowest cost in $/kWh at $165/kWh and $104/kWh, respectively, inclusive of BOP and C&C costs; PSH is more mature and efficient
- Redox flow batteries hold promise and there is room for improvement with stack optimization and better flow battery management algorithms
- Battery energy storage technologies serve a useful purpose by offering flexibility in terms of targeted deployment across the distribution system.





Conclusions

- A rapidly evolving grid space is leading to shifts in hydro and PSH operations; hydro and PSH offer enormous flexibility
- Economic value is highly dependent on siting and scaling of energy storage resources
- Among the battery systems, Li-ion offers the best option today in terms of cost, performance, calendar and cycle life, and technology maturity
- For longer-term storage, PSH and CAES give the lowest cost in $/kWh at $165/kWh and $104/kWh, respectively, inclusive of BOP and C&C costs; PSH is more mature and efficient
- Battery energy storage technologies serve a useful purpose by offering flexibility in terms of targeted deployment across the distribution system
- PSH offers more than 95% of U.S. energy storage capacity but there have been no new large projects in the last 20 years due to regulatory, economic, and environmental concerns
- The U.S. Department of Energy is working to address some of the key technical challenges to long-duration storage deployment in the U.S.

Acknowledgments

Dr. Sam Bockenhauer, DOE – Energy Efficiency and Renewable Energy, Water Power Technologies Office

Dr. Imre Gyuk, DOE – Office of Electricity, Energy Storage

https://www.energy.gov/eere/water/hydrowires-initiative
https://www.energy.gov/oe/activities/technology-development/energy-storage

Q/A and Further Information

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https://energystorage.pnnl.gov/