U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Linking Grid Services to Storage and Hydropower Plant Capabilities

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Discussion

- Hydropower and pumped storage as a useful lens
- **Linking technology characteristics to grid services**
- The motivation and immediate plans for a new research program (HydroWIRES) from US DOE Water Power Technologies Office

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HydroWIRES Initiative

Value Under Evolving System Conditions

What Will the Grid Require?

Output: Drivers, Services, and Value

Capabilities and Constraints

What Can the Hydropower Fleet Do, and Why, in Today's and the Emerging Grid?

Output: Technology Characterization

Operations and Planning

How Can We Plan and Operate the Hydropower Fleet to Best Take Advantage of Capabilities?

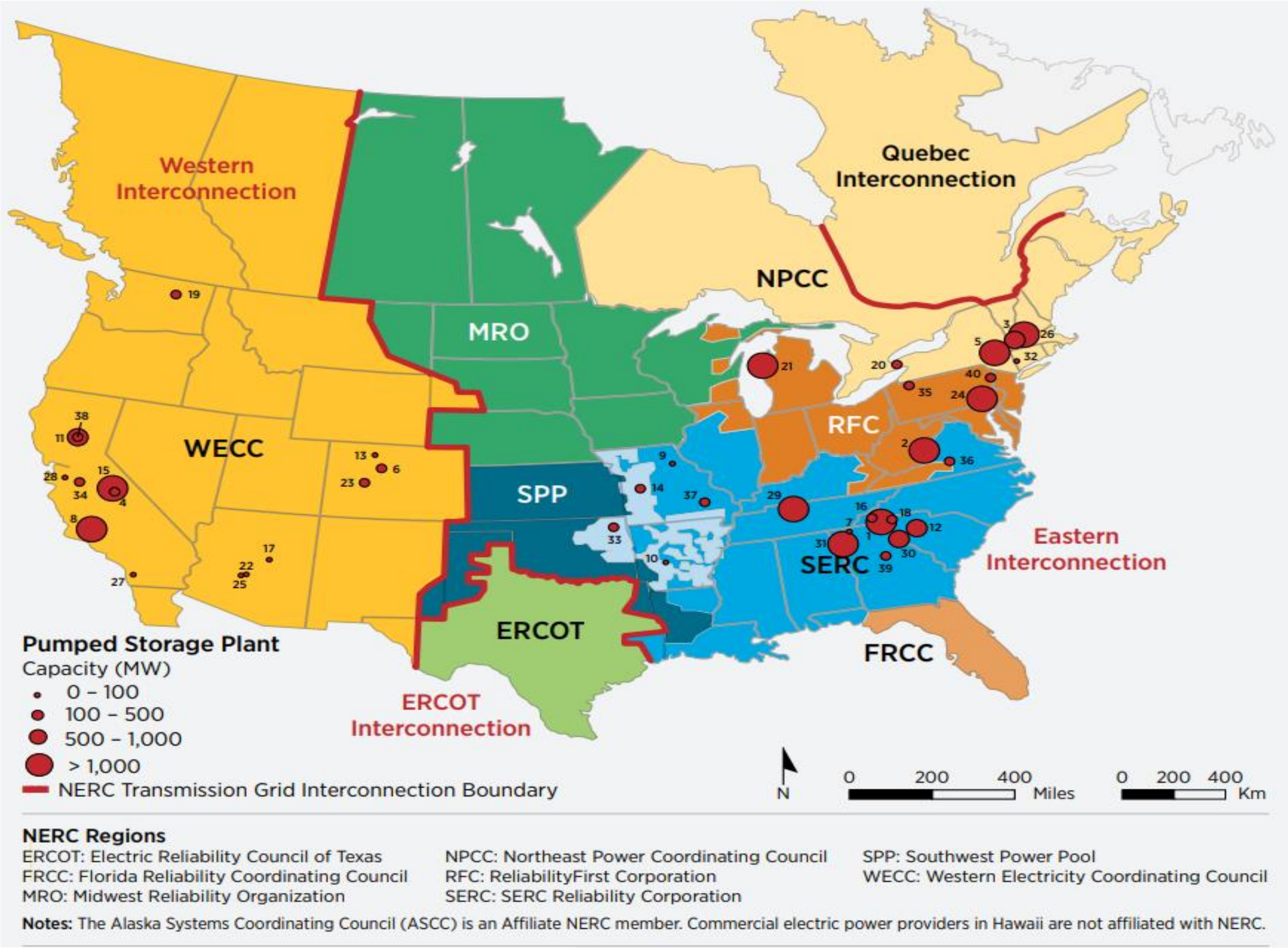
Output: Competitive Position and Contribution to System Attributes

Technology Innovation

What Achievable Innovations are Needed to Enable or Preserve Hydropower's Critical Contribution to the Electric System?

Output: New Technology Designs to Create New Capabilities or Remove Barriers

Pumped storage hydropower



Source: Argonne National Laboratory

Figure 2-41. Existing pumped storage hydropower plants in the United States

Pumped storage hydropower capacity (MW)	
Cumulative (end of 2016)	
CA	3,756
VA	3,109
SC	2,581
MI	1,979
TN	1,714
GA	1,635
PA	1,541
MA	1,540
NY	1,240
MO	600
CO	509
NJ	453
WA	314
OK	259
AZ	194
NC	95
CT	31
AR	28
UT	0.14
Remainder of United States	0
TOTAL	**21,578**

International development contrast

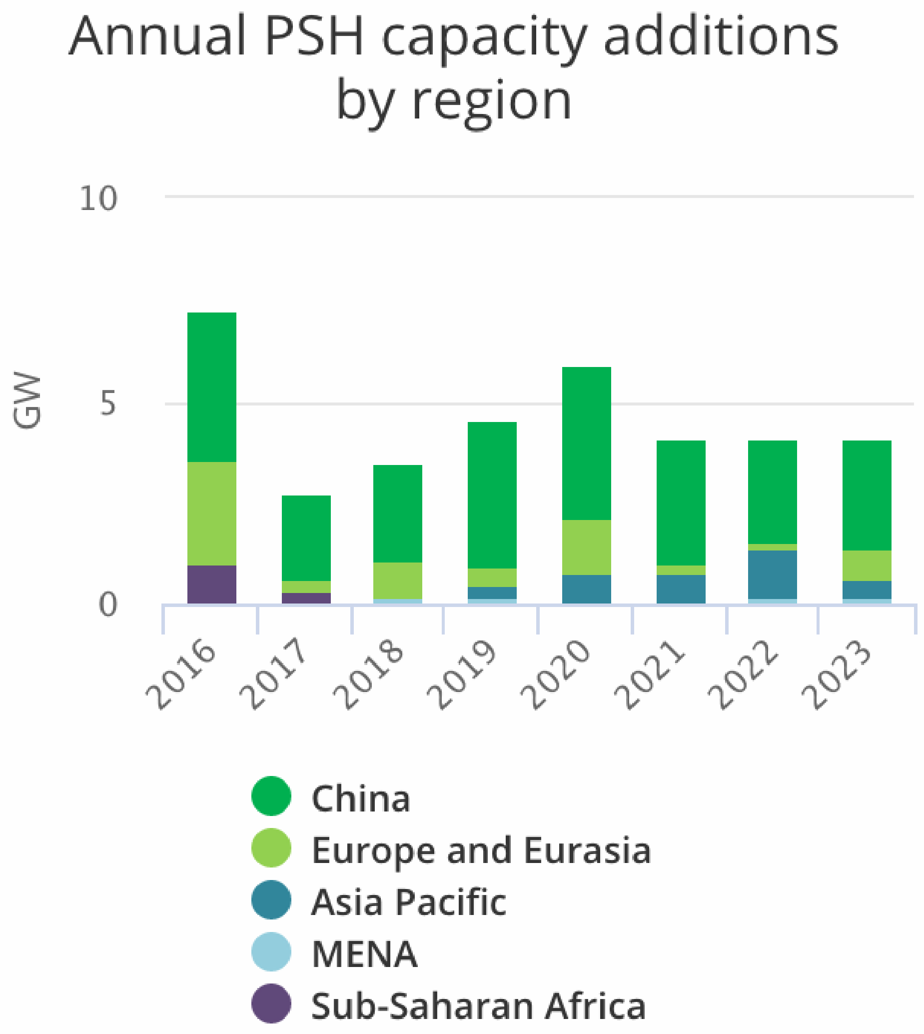


Table 2.1. Worldwide Deployment by Technology Type, 2018

Technology	MW Deployed
Sodium sulfur	189
Lithium-ion	1,629
Lead acid	75
Sodium metal halide	19
Flow battery	72
PSH	169,557
CAES	407
Flywheels	931
Electrochemical capacitor	49
Total	172,928

DOE Global Energy Storage Database, https://www.energystorageexchange.org/ 2018.

International Energy Agency, March 4 2019.
https://www.iea.org/newsroom/news/2019/march/will-pumped-storage-hydropower-capacity-expand-more-quickly-than-stationary-b.html

Changing operations to accommodate VRE

US DOE Hydropower Market Report 2018. https://www.energy.gov/eere/water/hydropower-market-report

AN EXAMPLE OF CHANGES IN PUMPED STORAGE HYDROPOWER OPERATIONS IN MARKETS WITH HIGH PENETRATIONS OF VARIABLE RENEWABLES: THE HELMS PROJECT IN CALIFORNIA

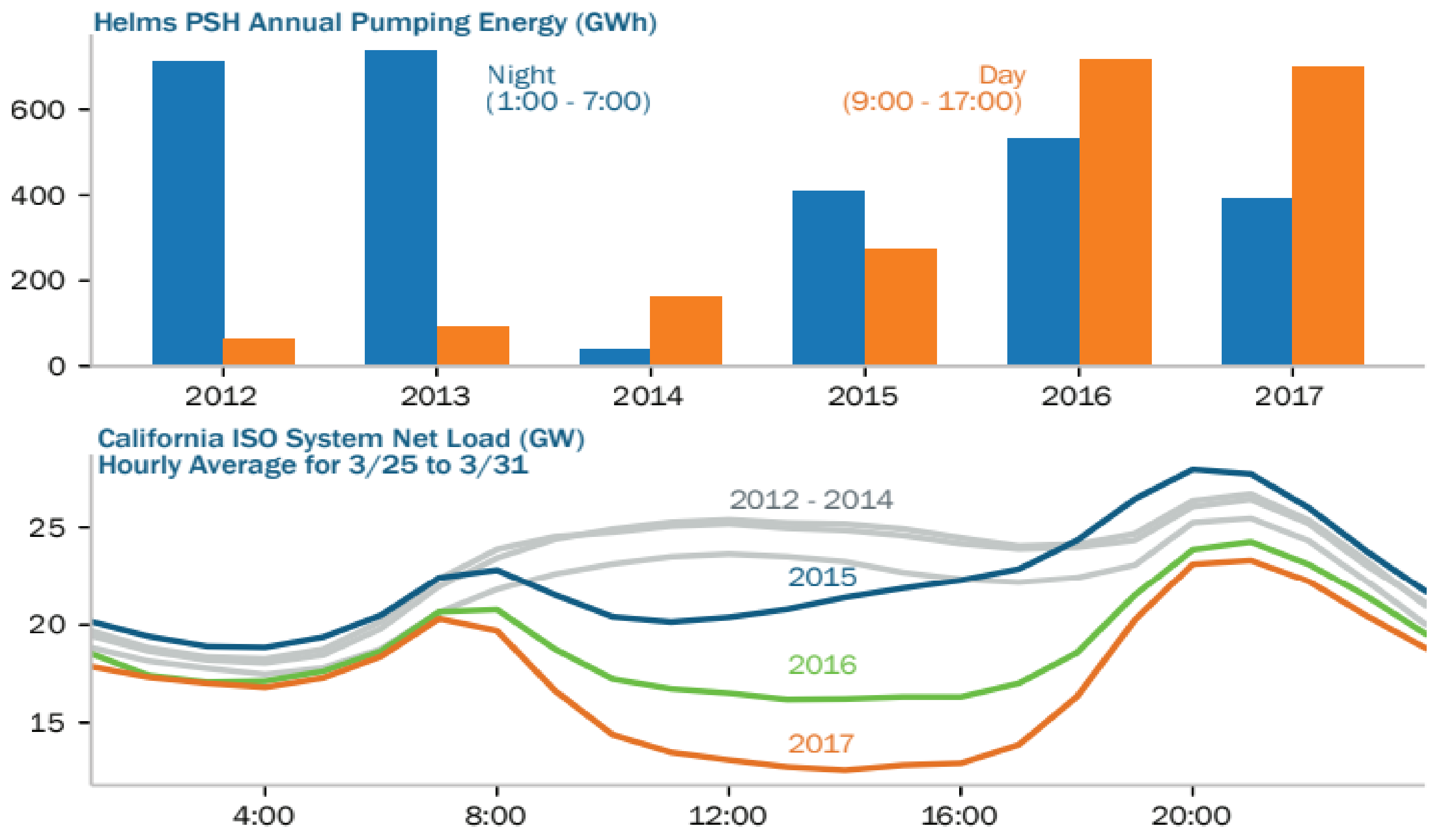


Figure 34. Annual pumping energy consumption by Helms PSH versus CAISO net load in the last week of March (2012-2017)

Comparing storage technologies by attribute

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

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

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

Break down storage into comparable performance attributes:

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

Energy Storage Technology and Cost Characterization Report, forthcoming from Pacific Northwest National Laboratory, Richland WA.

Comparable storage attributes

Parameter	Pumped Storage Hydropower [a]		
Capital Cost – Power ($/kW)	2,638[b]		
Power Conversion System ($/kW)	Included in Capital Cost		
Balance of Plant ($/kW)			
Construction and Commissioning ($/kW)			
Total Project Cost ($/kW)	2,640 [f]		
Total Project Cost ($/kWh)	165		
Operations and Maintenance (O&M) Fixed ($/kW-year)	15.9		
O&M Variable Cents/kWh	0.00025		
Round-Trip Efficiency (RTE)	0.8		
Annual RTE Degradation Factor			
Response Time	FS	AS	Ternary
Spinning-in-air to full-load generation	5-70 s	60 s	20-40 s
Shutdown to full generation	75-120 s	90 s	65-90 s
Spinning-in-air to full load	50-80 s	70 s	25-30 s
Shutdown to full load	160-360 s	230 s	80-85 s
Full load to full generation	90-220 s	280 s	25-60 s
Full generation to full load	240-500 s	470 s	25-45 s[g]

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

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

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

The challenge of valuing large pumped storage assets

Valuation Challenges
Act as either a generator or load
Current state is influenced by all previous states
Operational limitations and behaviors are not captured with single value specifications (nameplate capacity, energy)
Long-lived asset (40 years) requiring extended-term forecasted value
Long timeline from decision to commissioning (new projects)
Competition of limited energy for services, intertemporal competition
Scale influences prices

Valuation Methodologies Developed to Account for Grid Services
Capacity
Energy Arbitrage
Ancillary Services
Black Start
Power System Stability
System-Wide Effects
Transmission Services (Congestion Relief, Deferral)

Ideal Model Integration Features for Pumped Storage Valuation
Estimation of system effects due to the operation of the PSH unit
Performance characterization (non-linearity, “SOC,” economic plant life)
Account for forecast uncertainties
Mathematical optimization considering all possible services simultaneously

Pumped Storage Hydropower Valuation Guidebook, forthcoming technical report from Argonne National Laboratory, Lemont IL.

Relevant Modeling Tools Required for Co-Optimization, Compared
Energy Storage Valuation
Production Cost and Capacity Expansion
Hydropower Simulation and Water Allocation
Transmission System Planning
Agent-Based Electricity Market Simulation

Storage within transmission planning

Transmission Planning Region	Planning Region Type	Regional Transmission Planning Cycle	Solution Procurement Type
California ISO (CAISO)	ISO/RTO	15 months	Competitive bidding
Columbia Grid	Non-ISO/RTO	Two years	Sponsorship
Florida Reliability Coordinating Council (FRCC)	Non-ISO/RTO	Two years	Sponsorship
ISO New England (ISO-NE)	ISO/RTO	Not defined	Sponsorship
Midcontinent ISO (MISO)	ISO/RTO	18 months	Competitive bidding
New York ISO (NYISO)	ISO/RTO	Two years	Sponsorship
Northern Tier Transmission Group (NTTG)	Non-ISO/RTO	Two years	Sponsorship
PJM (PJM)	ISO/RTO	Two years	Sponsorship
South Carolina Regional Transmission Planning (SCRTP)	Non-ISO/RTO	Two years	Sponsorship
Southeastern Regional Transmission Planning (SERTP)	Non-ISO/RTO	One year	Sponsorship
Southwest Power Pool (SPP)	ISO/RTO	Three year	Competitive bidding
WestConnect	Non-ISO/RTO	Two year	Competitive bidding

Recommendations for future work:

- Cost-effectiveness analysis for ATS (alternative transmission solution) considering unique characteristics
- Market participation models for "dual use" (market + transmission)
- Storage optimization and cost-recovery mechanisms

Role of Large-Scale Energy Storage in Transmission Planning, forthcoming report from Argonne National Laboratory, Lemont IL.

Technology characteristics to grid services

	Hydro (conventional; large units)	Hydro (pumped storage)	Combustion turbine	Combined cycle	Coal or other fossil fuel (thermal)
Go/no-go requirements					
Able to start without an outside electrical supply (fundamental requirement)	Yes (if so equipped).	Yes (if so equipped)	Yes (if so equipped)	Yes (if so equipped)	Yes (if so equipped)
Sufficient real power capability	Yes (if so equipped)	Yes (if so equipped)	Yes (if so equipped)	Yes (if so equipped)	Yes (if so equipped)
Sufficient reactive power capability	Yes (if so equipped)	Yes (if so equipped)	Yes (if so equipped)	Yes (if so equipped)	Yes (if so equipped)
Required attributes					
Short starting time (less is better)	Sub-hour	Sub-hour	Sub-hour	Hours	Many hours
Number of units at black start facility	Many units typical at larger plants	Usually several units	Usually several units	Usually several units	Often more than one unit
On-site fuel inventory of black start fuel	Ample fuel (water) nearly always available unless impacted by drought conditions	Fuel (water) would need to be held in reserve for black start purposes	Fuel available if pipeline remains in service and pressurized	Fuel available if pipeline remains in service and pressurized	Fuel (local coal pile) nearly always available but must be pulverized
Complexity of necessary auxiliary systems (e.g., fuel supply, cooling, emission controls)	Very simple	Very simple	Simple	Somewhat complex thermal systems	Very large and complex thermal systems

Hydropower Plants as Black Start Resources, forthcoming technical report from Oak Ridge National Laboratory, Oak Ridge TN.

Hydropower utilization as a ramping resource today

Hydropower's ability to quickly adjust output up or down to follow changes in net load plays a key role in complement to the much larger, and also highly flexible, natural gas fleet.

US DOE Hydropower Market Report 2018. https://www.energy.gov/eere/water/hydropower-market-report

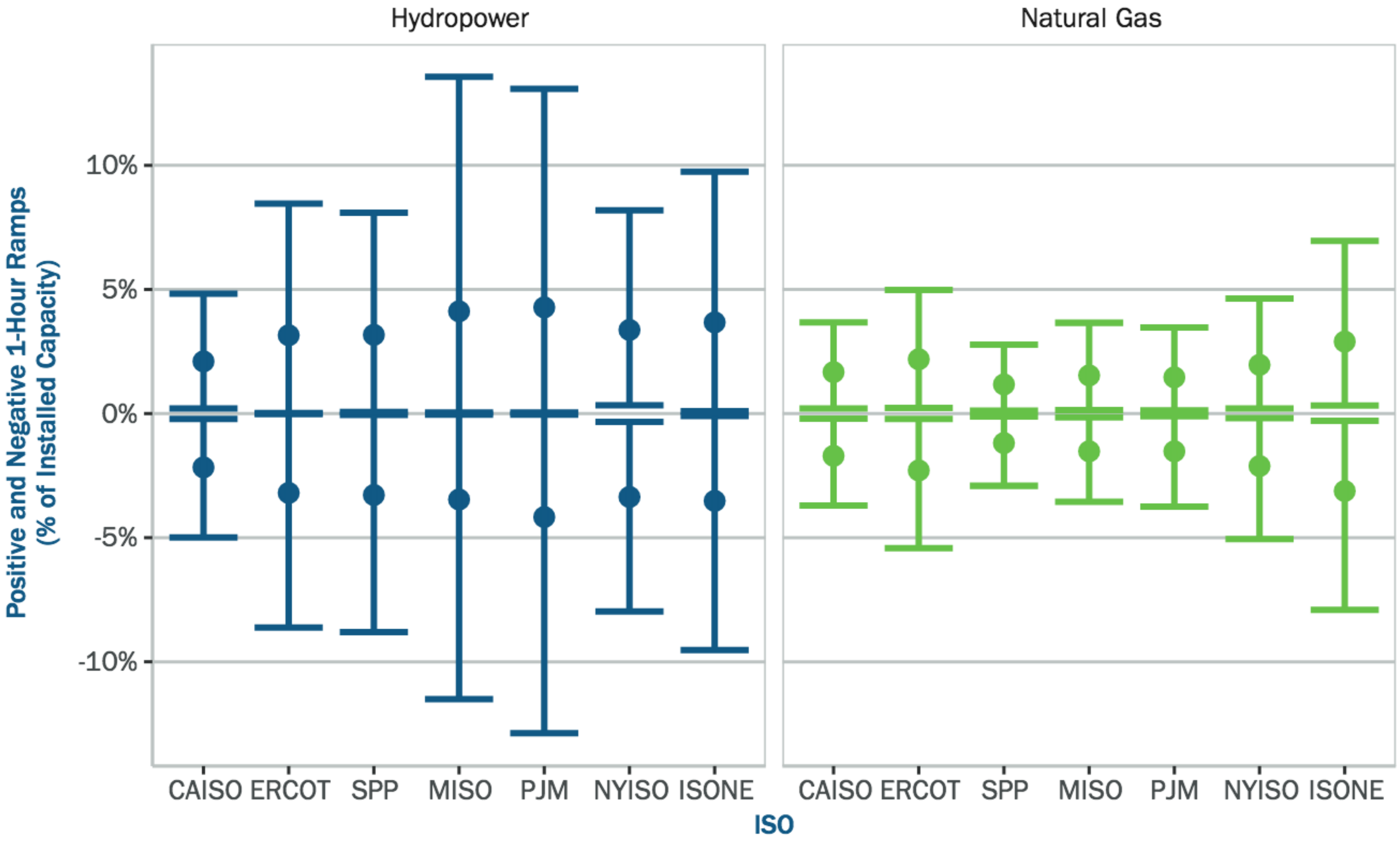
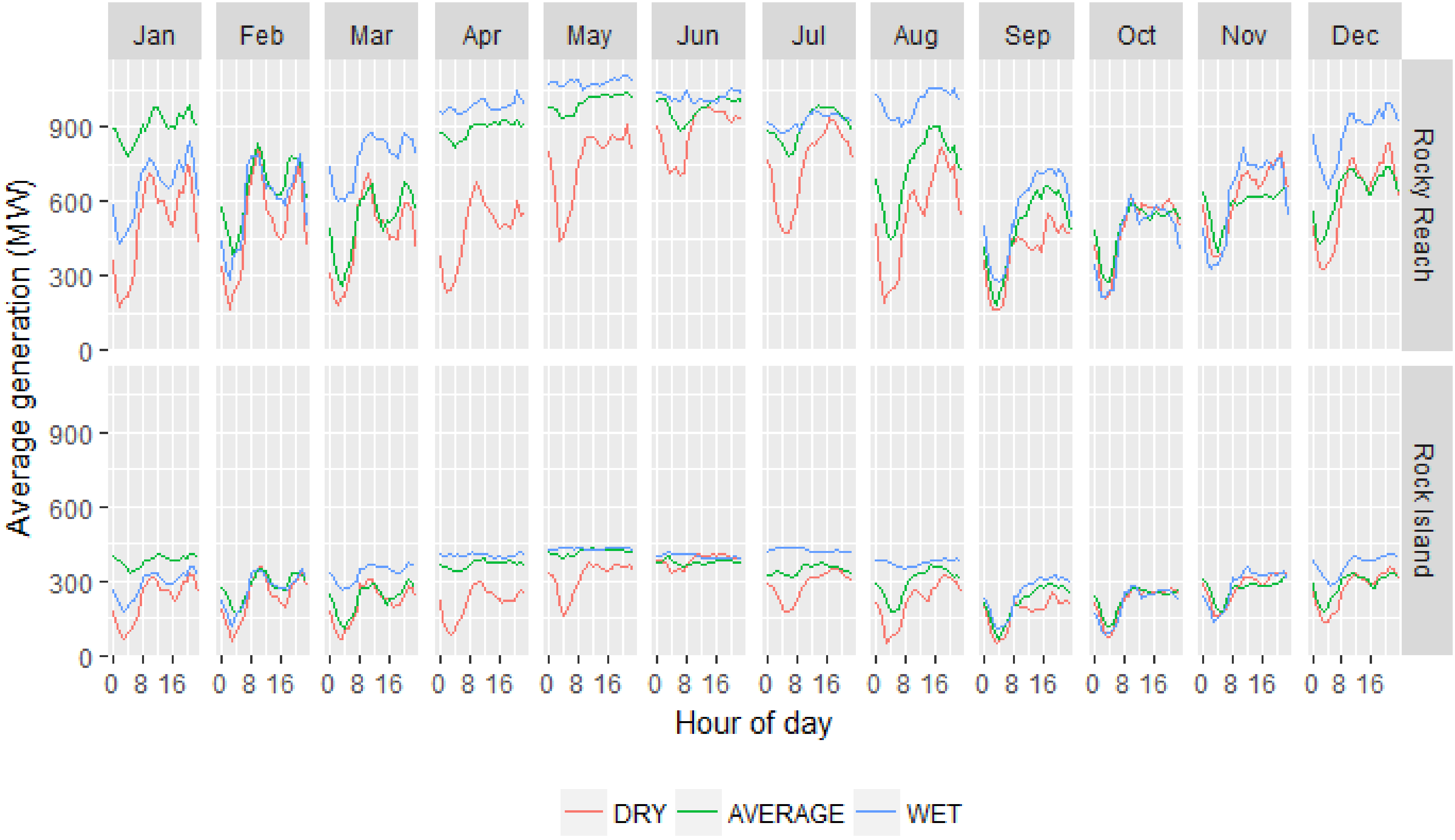


Figure 4. Average and 10th-90th percentile interval for one-hour ramps (both positive and negative) per installed megawatt for hydropower and pumped storage hydropower vs. natural gas by ISO/RTO

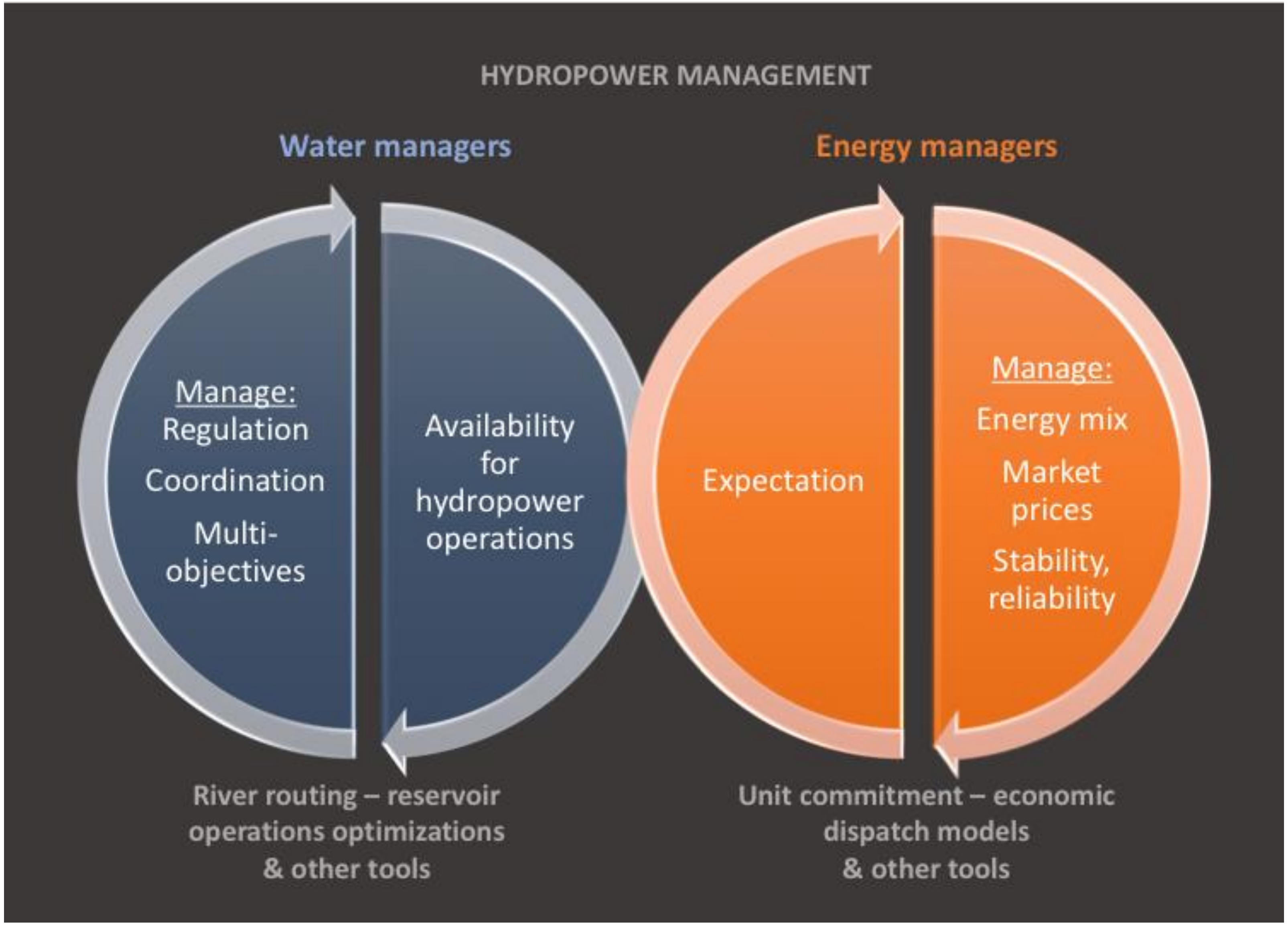
Range of hourly to seasonal flexibility from hydropower

Illustration of hydropower flexibility over multiple temporal scales provided by varying generation over hours, days, months and seasons to meet market opportunities and local demands, managed in concert with water availability.



Hydropower Value – Chelan PUD Case Study. Forthcoming publication from Pacific Northwest National Laboratory in collaboration with Chelan County Public Utility District #1, Wenatchee, WA.

Hydropower: marrying water and energy management



Understand the current state of representation of hydropower in power system models, including challenges of effective characterization of hydropower assets and seams between electricity dispatch and water management models.

Improving hydropower representation in power system models. Forthcoming workshop report from National Renewable Energy Laboratory and Pacific Northwest National Laboratory.

The role of research : anticipated near-term DOE actions

- **New tools and modeling enhancements**
  - Pumped storage valuation software tool
  - Improved characterization of hydropower, or precise sense of the limitations (spatial, temporal, units, computational complexity)
  - Modeling enhancements for pumped storage
- **Data development**
  - Quantification of hydropower fleet operational flexibility, potential and available
  - Plant and fleet-level conditions and capabilities
- **Improving hydropower's competitive position**
  - Advanced plant capabilities
  - Development timeframe reduction

Please help us! Respond to a Request for Information (to issue in April) and provide feedback on the HydroWIRES research roadmap.

Thank you

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BACKUP SLIDES

Grid Flexibility, Reliability and Resilience for Hydropower

We support research to evaluate and improve the ability of hydropower to provide **essential flexibility and reliability services** for the rapidly evolving electric grid

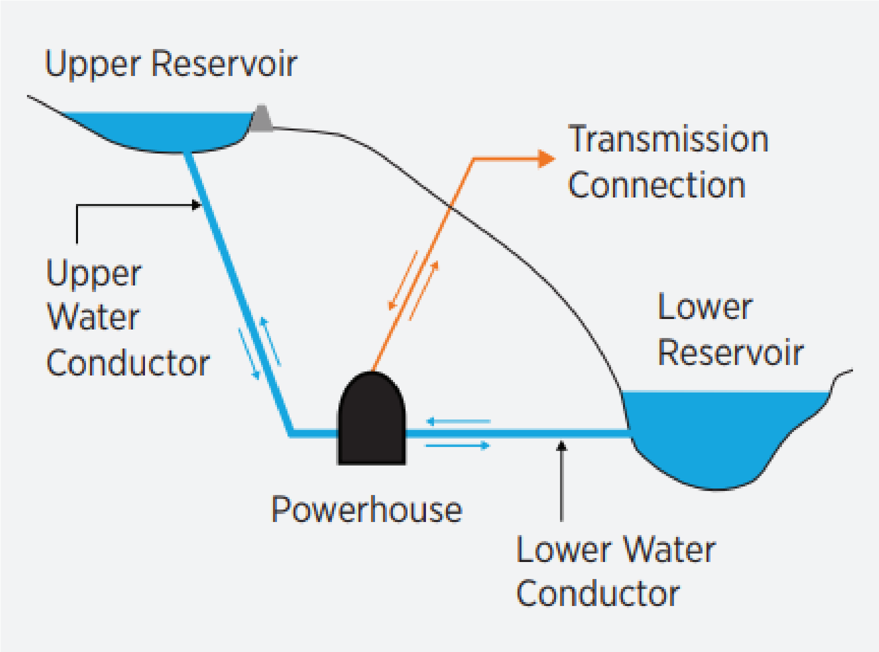
- Understand baseline conditions of hydropower and pumped storage contribution to grid reliability and resiliency
- Assess the costs and opportunities of operating hydropower flexibly
- Improve capabilities to evaluate future grid system conditions and services that hydropower and pumped storage are well suited to provide
- Preserve and enable competitive hydropower flexibility
- Support development of innovative hydropower and pumped storage technologies

Pumped Storage Hydropower

- Pumped-storage hydropower (PSH) is a **water battery**:
  - Two water reservoirs are configured at different elevations that can generate power (**discharge**) as water moves down through a turbine; and that draws power as it pumps water (**recharge**) to the upper reservoir.

- Projects may be:
  - **Open loop** – There is an ongoing hydrologic connection to a natural body of water
  - **Closed loop** – Reservoirs are not connected to an outside body of water

- Pumped storage hydropower characteristics:
  - 97% of domestic energy storage (22 GW)
  - Large (>100 MW), long duration
  - Historically built for daily swings in load and as a companion
  to large thermo-electric generators
  - Flexible resource that supports reliability objectives

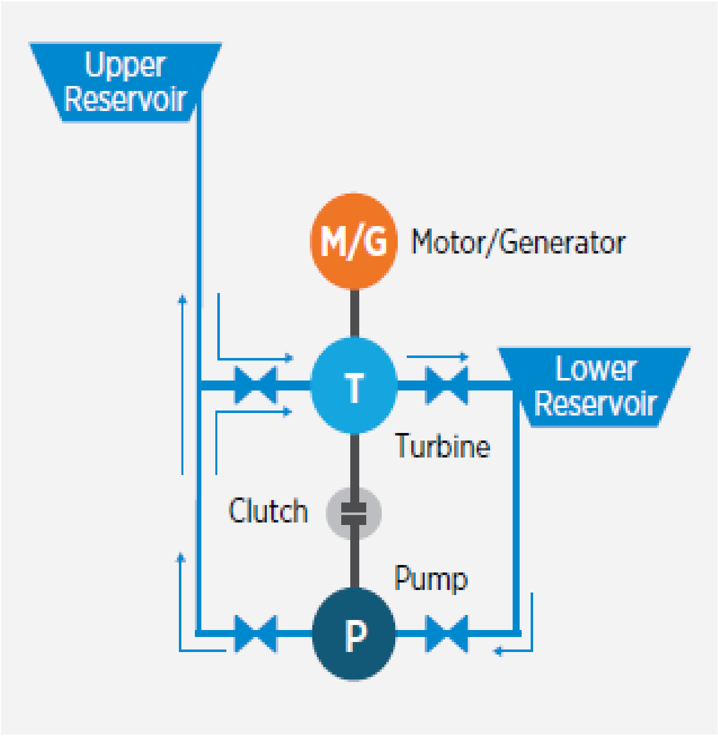


Source: Koritarov et al. 2014 [234]

Figure 2-42. Typical configuration of a pumped storage hydropower plant

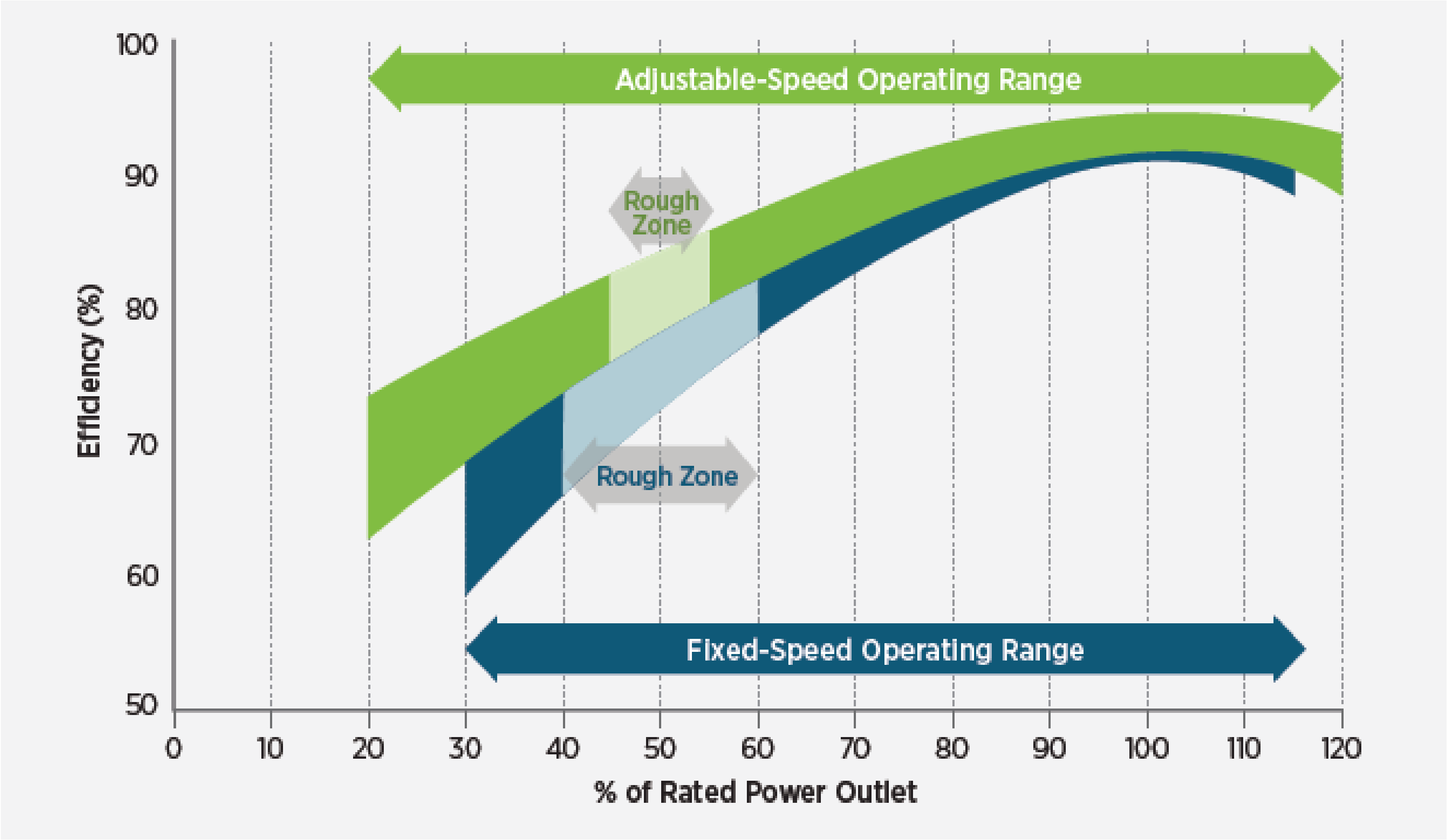
Operating Ranges and Alternate Configurations

- Pumped storage round-trip or cycle energy efficiencies are typically around 75%



Source: Koritarov et al. 2013b [237]

Figure 2-45. Typical configuration of a ternary pumped storage hydropower with hydraulic bypass



Source: Koritarov et al. 2014 [83], adapted from Corps 2009 [235]

Figure 2-43. Generation efficiency curves for fixed-speed (blue) and adjustable-speed (green) pumped storage hydropower units

Typical Operating Characteristics of Alternate Configurations

Capability	Fixed-Speed PSH	DFIM Adjustable-Speed PSH	Ternary PSH with Hydraulic Bypass and Pelton Turbine
Generation Mode:			
Power output (% of rated capacity)	30%[a]–100%	20%–100%	0%–100%
Standstill to generating mode (seconds)	75–90	75–85	65
Generating to pumping mode (seconds)	240–420	240–415	25
Frequency regulation	Yes	Yes	Yes
Spinning reserve	Yes	Yes	Yes
Ramping/load following	Yes	Yes	Yes
Reactive power/voltage support	Yes	Yes	Yes
Generator dropping	Yes	Yes	Yes

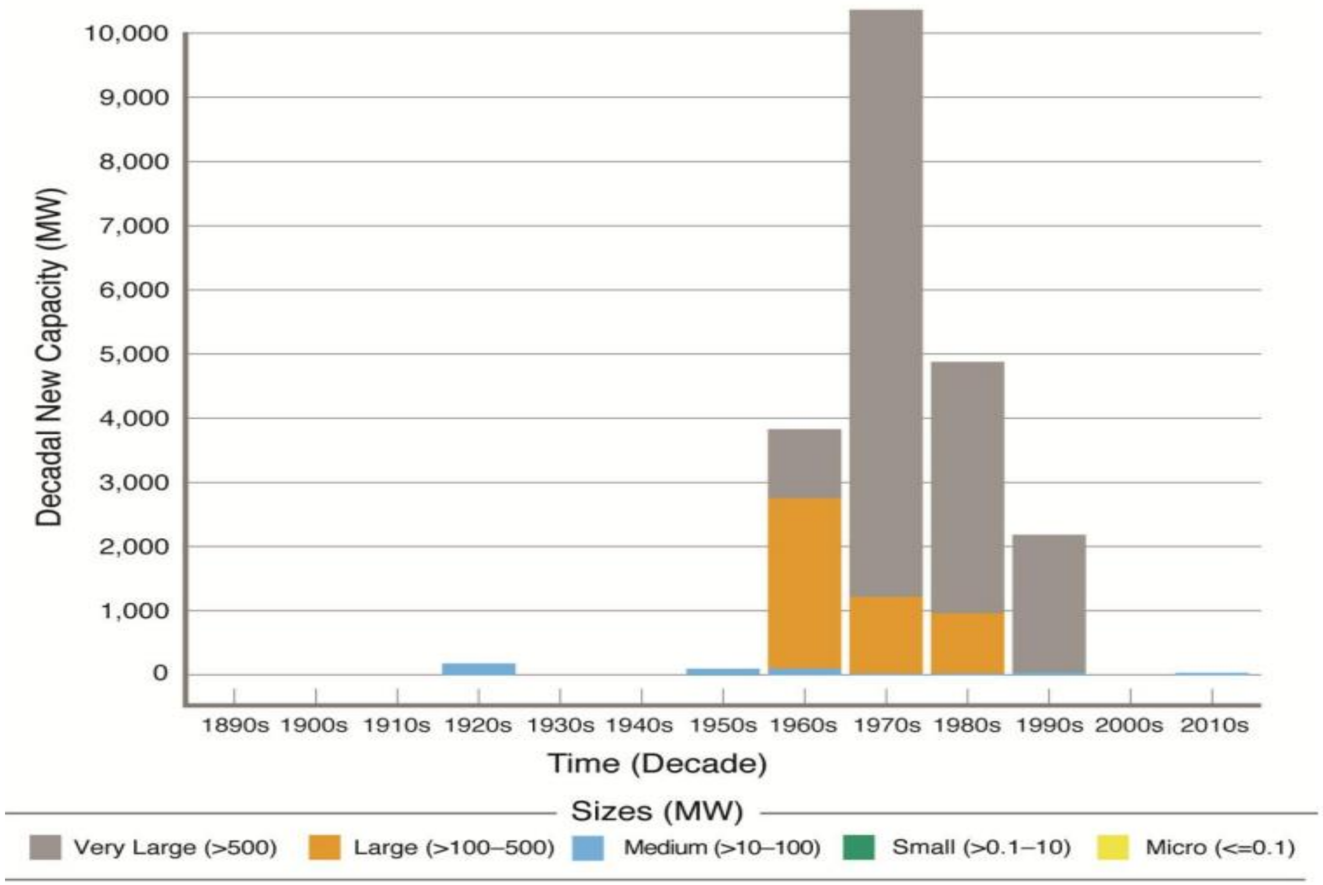
Capability	Fixed-Speed PSH	DFIM Adjustable-Speed PSH	Ternary PSH with Hydraulic Bypass and Pelton Turbine
Pumping Mode:			
Power consumption (% of rated capacity)	100%	60%-100% (75%-125%)[b]	0%-100%
Standstill to pumping mode (seconds)	160–340	160–230	80
Pumping to generating mode (seconds)	90–190	90–190	25
Frequency regulation	No	Yes	Yes
Spinning reserve	No	Yes	Yes
Ramping/load following	No	Yes	Yes
Reactive power/voltage support	Yes	Yes	Yes
Load shedding	Yes	Yes	Yes

a. One of the key factors determining the minimum power output is the hydraulic head. While fixed-speed PSH with high head can have the minimum as low as 20% of rated capacity, 40% is a more realistic value for medium to lower head PSH units.

b. If a PSH unit is converted from fixed- to adjustable-speed and the same pump-turbine runner is used, the power consumption may range from 75% to 125% of the former fixed-speed power consumption (100%).

Source: Koritarov et al. 2015 [238]

Development curve



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

New Funding Opportunity for Pumped Storage

DE-FOA-0001836: Innovative Design Concepts for Standard Modular Hydropower and Pumped-Storage Hydropower

In August 2018, WPTO released a new funding solicitation for pumped storage hydropower on two topics:

– Innovative design concepts that can reduce costs of deployment, expand siting access, speed the time to commissioning, and provide additional non-electric value streams

– Analysis and modeling enhancements that illustrate how pumped storage can improve electricity system resilience, reliability, and economic efficiency

Concept paper deadline: September 28, 2018

https://www.energy.gov/eere/water/articles/funding-available-innovative-design-concepts-standard-modular-hydropower-and